AD-A059 024 COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER N H F/G 8/12
PREFERRED CRYSTAL ORIENTATIONS IN THE FAST ICE ALONG THE MARGIN--ETC(U)
JUN 78 W F WEEKS, A J GOW NOAA ORDER-01-5-022-165
UNCLASSIFIED CRREL-78-13 NL

| OF |

AD
A059024

END
DATE
FILMED
11-78
DDC

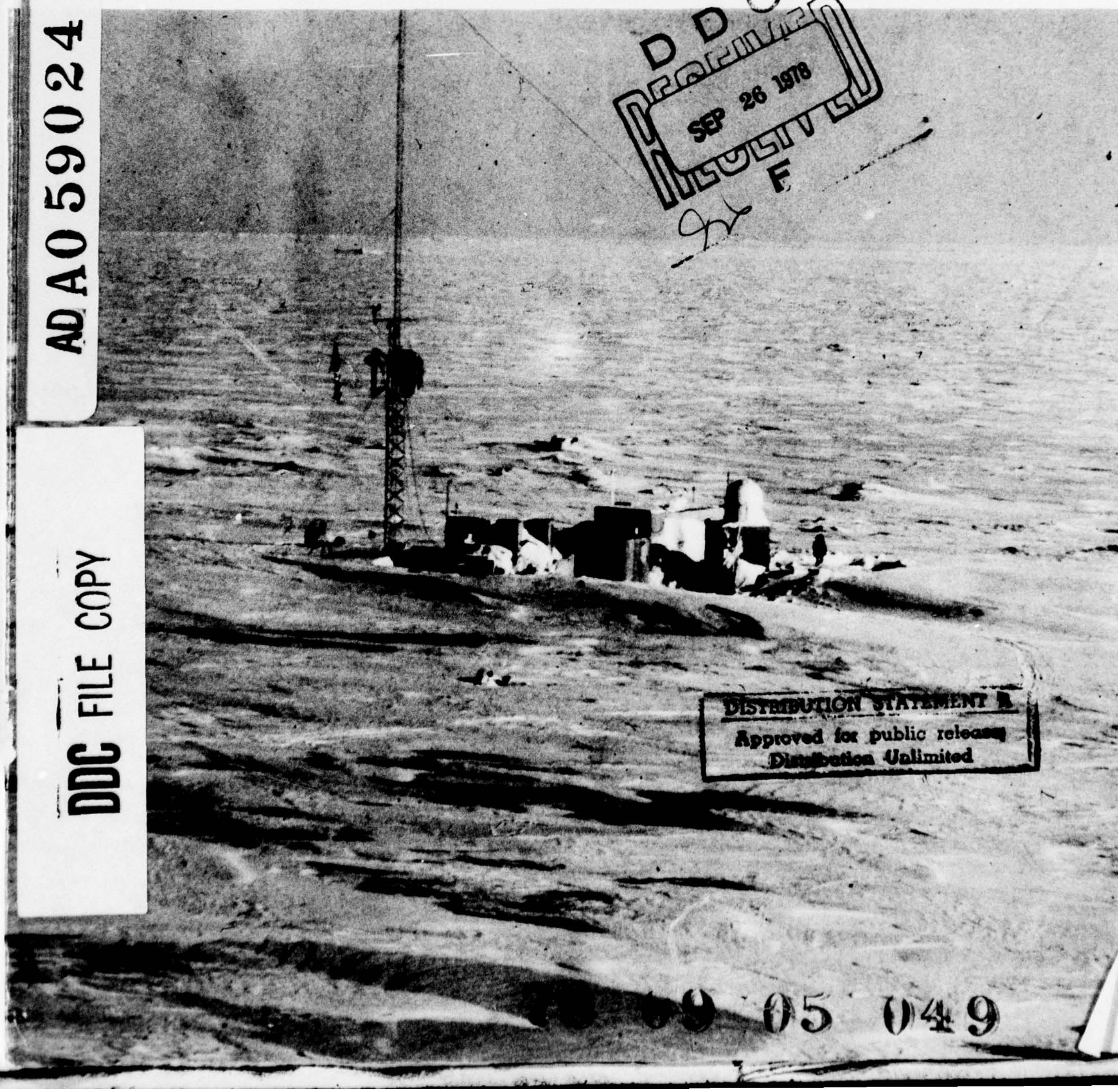
CRREL

REPORT 78-13

12

LEVEL II

Preferred crystal orientations in the fast ice along the margins of the Arctic Ocean



For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

Cover: The CRREL camp on Narwhal Island was the base from which the observations reported here were made. The island itself is small (see Fig. 9) and is surrounded by a broad expanse of fast ice. (Photograph by A.J. Gow.)

14

CRREL [redacted]-78-13

6

Preferred crystal orientations in the fast ice along the margins of the Arctic Ocean,

10

W.F. Weeks [redacted] A.J. Gow

11

Jun[redacted]78

12 32p.

15 NOAA Order-01-5-022-2651

Prepared for
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
By
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
U.S. ARMY CORPS OF ENGINEERS
HANOVER, NEW HAMPSHIRE

037 100

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER CRREL Report 78-13	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PREFERRED CRYSTAL ORIENTATIONS IN THE FAST ICE ALONG THE MARGINS OF THE ARCTIC OCEAN		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) W.F. Weeks and A.J. Gow		8. CONTRACT OR GRANT NUMBER(s) NOAA Order No. 01-5-022-1651 Research Unit 88
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS National Oceanic and Atmospheric Administration Washington, D.C.		12. REPORT DATE June 1978 13. NUMBER OF PAGES 29
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This study was supported by the Bureau of Land Management through Interagency agreement with the National Oceanic and Atmospheric Administration.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Arctic Ocean
Crystals
Ice
Orientation (direction)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Field observations of the growth fabrics of the fast and near-fast ice along the coasts of the Beaufort and Chukchi Seas show that, at depths of more than 60 cm below the upper ice surface, the sea ice crystals show striking alignments within the horizontal plane. At one site this alignment was well developed at a depth of 15 cm and in all cases the degree of preferred orientation increased with depth, with the strongest orientations occurring at the bottom of the ice sheet. In general the c-axes of the crystals were aligned roughly E-W parallel to the coast. In the vicinity of islands the alignment roughly paralleled the outlines of the islands and in narrow passes between islands the alignment paralleled the channel. Our observations, as well as similar observations made in the Kara Sea by Cherepanov, can be

Cont.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract (cont'd)

cont'd

explained if it is assumed that the c-axes of the crystals are aligned parallel to the "long-term" current direction at the sea ice/sea water interface. The alignments are believed to be the result of geometric selection among the growing crystals, with the most favored orientation being that in which the current flows normal to the (0001) plates of ice that make up the dendritic ice/water interface characteristic of sea ice. It is hypothesized that current flow in this direction reduces the thickness of the solute boundary layer as well as the salinity in the liquid at the interface. This lowered salinity allows crystals in the favored orientation to extend farther into the melt than neighboring crystals with less favored orientations. In addition the current tends to induce a continuous flux of supercooled seawater against the sides of the crystals that extend ahead of the interface. This favors their lateral growth. The aligned crystal aggregate that forms has the overall characteristics of a single crystal. The development of such crystal alignments results in pronounced anisotropy in the mechanical, thermal, and electrical properties of fast ice. It is suggested that such crystal orientations can be used as an aid in determining current patterns in perennially ice-covered areas such as the Canadian Archipelago.

PREFACE

This report was prepared by Dr. W.F. Weeks, Glaciologist, and Dr. A.J. Gow, Geologist, of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

The work covered by this report was funded under National Oceanic and Atmospheric Administration Order No. 01-5-022-1651, *Dynamics of Near Shore Sea Ice*; Research Unit 88, *Outer Continental Shelf Environmental Assessment Program*.

This study was supported by the Bureau of Land Management through interagency agreement with the National Oceanic and Atmospheric Administration, under which a multi-year program responding to needs of petroleum development of the Alaskan continental shelf is managed by the Outer Continental Shelf Environmental Assessment Program (OCSEAP). This particular study would not have been possible without the support of G. Weller and T. Flesher of the Arctic OCSEAP in Fairbanks.

The technical content of this report was reviewed by Dr. W.D. Hibler III and Dr. G.D. Ashton of CRREL.

The authors would like to thank Dr. G.D. Ashton, Dr. S.C. Colbeck, A. Kovacs, and S. Martin for their helpful comments on a draft of this report. G. Burton of NAVOCEANO kindly provided them with the magnetic field calculations for the Kara Sea. J. Kelly assisted with the field work, and R. Labounty and J. Barnhill with helicopter support.

CONTENTS

ILLUSTRATIONS

TABLES

PREFERRED CRYSTAL ORIENTATIONS IN THE FAST ICE ALONG THE MARGINS OF THE ARCTIC OCEAN

W.F. Weeks and A.J. Gow

INTRODUCTION

The structure of the initial ice layer that forms when seawater begins freezing is largely controlled by the ambient meteorological and oceanographic conditions. If conditions are calm, the ice crystals are plate or starlike (hexagonal), with the plane of the plate or star being the basal (0001) plane of the ice crystal. Because of their tabular nature such crystals tend to float with their basal planes oriented parallel to the water surface. This results in an ice skim with a predominantly c-axis vertical orientation. Crystals with other c-axis orientations are, however, invariably also present. When sea conditions are not calm, the motion of the water reduces the effective thermal supercooling, more crystals form per unit volume of seawater, and the abrasive action between crystals causes the arms of the stars to fracture and the crystals in general to be more rounded. The result is a surface layer of frozen slush that is fine-grained, equigranular in texture, with a random or near-random c-axis orientation. At sites where wave action is pronounced, this layer of slush may be several tens of centimeters thick.

Once a continuous ice cover is established across the sea surface, the ice crystals at the advancing ice/water interface lose a degree of growth freedom. Only if the grain boundaries are exactly perpendicular to the freezing interface can growth proceed without a crystal interfering with the growth of its neighbors. If the ice crystals show a preferred growth direction, then it is to be expected that crystals initially oriented with that direction near vertical would be able to grow slightly ahead of, and ultimately cut off, other crystals from the melt (i.e.,seawater). This process is referred to as geometric selection. Inasmuch as ice crystals forming from seawater do show highly anisotropic growth, geometric selection is observed to occur, with the favored surviving crystals having their c-axes oriented in the horizontal plane (Perey and Pounder 1958, Kvajić et al. 1973). The portion of the ice sheet within which the c-axis horizontal orientation develops has been called the transition zone. The process of selective growth is quite efficient; therefore, the transition zone is usually only a few (~10 to 15) centimeters thick. The exact location of the transition zone within the ice sheet depends upon the location of the base of the initial ice layer (e.g., the zone could occur between 1 and 10 cm or between 50 and 65 cm).

Below the transition zone sea ice shows all the characteristics associated with the so-called columnar zone in metal ingots, i.e., pronounced crystal elongation parallel to the direction of heat flow, a strong crystal orientation, and an increase in crystal size as measured in the horizontal plane over crystals higher in the ice sheet. Figure 1 shows a photomicrograph of a vertical thin section of ice from the upper part of the columnar zone. In the few cases that have been studied (Weeks and Hamilton 1962, Tabata and Ono 1962, Weeks and Assur 1967), the average grain diameter increased as a linear function of depth. However, observations were not made below 60 cm because of the large number of crystals that were incompletely contained in a given thin section. Extrapolation of the available data suggested grain diameters of the order of 7 to 8 cm at the base of a 2-m-thick ice sheet. In the columnar zone the favored crystals surviving at the bottom of the ice sheet were believed to be those c-axis horizontal crystals that were oriented with their a-axes vertical. However, detailed studies have not been made to verify this.

The few fabric diagrams that were prepared from columnar zone ice appeared to show the c-axes distributed randomly in the horizontal plane. However, as with the grain size studies, fabrics were prepared of ice obtained only from the upper part of the ice sheet. When an ice core from the lower portion of the ice sheet showed a strong preferred crystal orientation within the horizontal plane, it was assumed to be caused

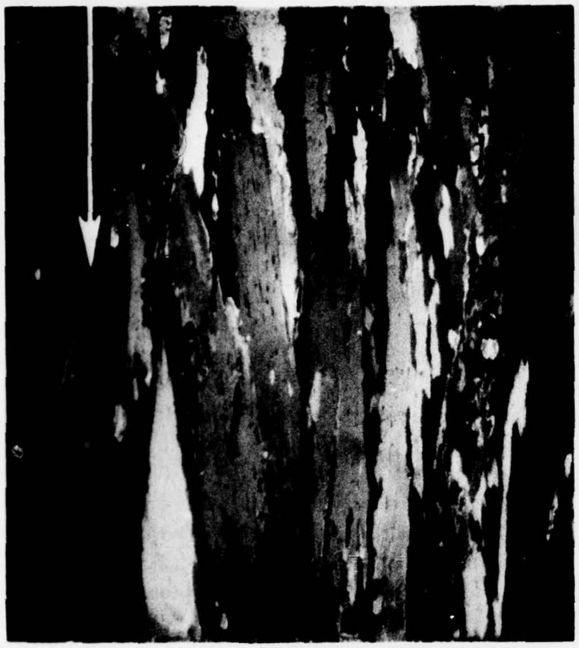


Figure 1. Vertical thin section of ice from the upper part of the columnar zone; Site 15, 47 to 57 cm. Note the pronounced elongation of the crystals parallel to the direction of growth (arrow).

by the sample largely coming from within one single crystal because the core diameters and the expected crystal diameters were about the same (~8 cm). The resulting conceptual picture of sea ice was of a material showing pronounced changes in physical properties with changes in the vertical location of the sample in the ice sheet, largely produced by changes in the amount of brine found within the ice, but with the properties being independent of direction in the horizontal plane if samples larger than several crystal diameters were used, i.e., a transversely isotropic material. A more detailed discussion of much of the above with accompanying references can be found in Weeks and Assur (1967).

However, information began to slowly accumulate that suggested that the above description of crystal orientation in sea ice might not be completely correct. For instance, Cherepanov (1964) and Smith (1964) observed that the old sea ice incorporated into ice islands SP-6 and Arlis II exhibited nearly perfect alignment of c-axes over large areas. In fact, all the ice in the 80-km² SP-6 showed a strong c-axis alignment. Then Peyton (1966) reported examining a 3- × 3-m block of 1.6-m-thick fast ice from near Barrow and finding that the bottom meter exhibited a constant c-axis orientation over the entire 9-m² cross section. Whether or not the entire area was a single crystal was not clear. Next, a most remarkable report of preferred c-axis alignments in sea ice was made by Cherepanov (1971), who observed conditions of nearly constant c-axis alignment over areas of hundreds of square kilometers in the Kara Sea. Finally, indirect evidence based on studies of the directional dependence of the electrical properties of sea ice collected at widely separated sites in the Canadian Arctic by Campbell and Orange (1974) and by Kohnen (1976) also tended to support Cherepanov's observations that oriented crystal structures might extend over lateral distances on the order of tens of kilometers.

In April 1976 Gow and Weeks (1977) examined the orientation of the sea ice crystals in a 1- × 1-m block of a 2.15-m-thick sheet of first-year sea ice at a site located just offshore of one of the barrier islands along the Beaufort Sea coast north of Prudhoe Bay, Alaska, to see if similar preferred orientations were present. The observations showed the c-axis orientation to be dominantly horizontal in all ice below 14 cm with a pronounced east-west preferred orientation developing within the horizontal plane by a depth of 26 cm. The present study is an extension of the above work in which we examine the areal variability of preferred c-axis orientations over a 60-km reach along the coast of the North Slope, compare the results with Soviet observations made in the Kara Sea, and discuss the possible controlling factors as well as the implications of such striking ice fabrics for future sea ice studies and for crystal growth research in general.

LOCALE AND TECHNIQUES

This work was carried out as a secondary program associated with an effort to measure the movement of near-shore sea ice along the coast of the Beaufort Sea using radar transponders and laser ranging systems (Weeks et al. 1977, Tucker et al. 1978). The base camp and one master radar unit of the ice movement system were located on Narwhal Island, the westernmost of the McClure Islands, and the other master unit was located on Cross Island (see Fig. 2). Cross and Narwhal Islands are representative of a number of barren, elongated gravel islands that compose the barrier islands that occur

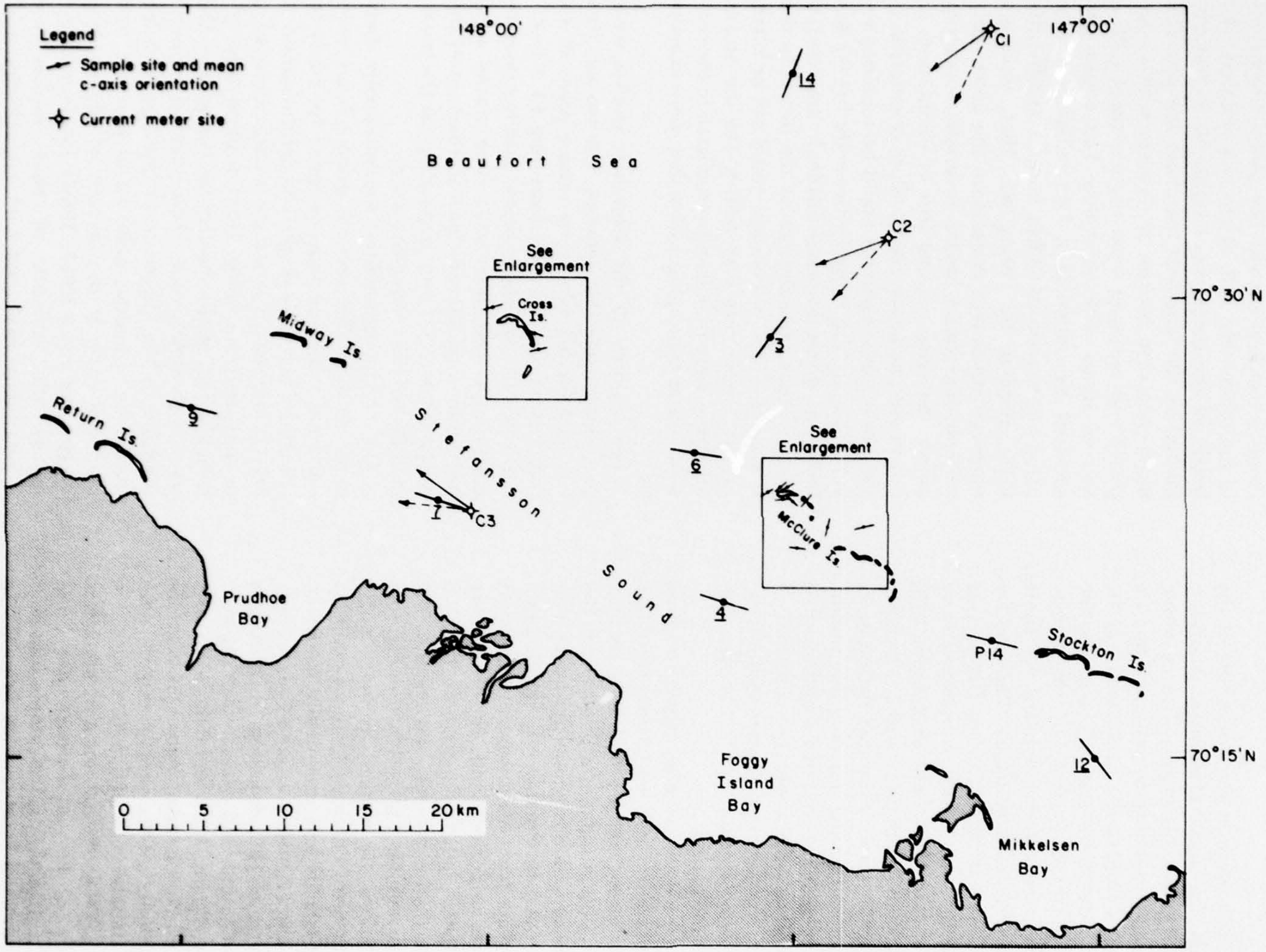


Figure 2. Map of Beaufort Sea coast in the vicinity of Prudhoe Bay, Alaska, showing sampling sites and mean c-axis orientation in the horizontal plane at each site. The two vectors pointing from the three current meter sites indicate the average current direction at the depth of the current meter (solid arrows) and a corrected current direction at the ice/water interface (dashed arrows), assuming a turning angle in the Ekman layer of 24°. Enlargements giving c-axis orientations in the vicinity of Cross Island and the McClure Islands are shown in Figures 8 and 9.

along, and help to shelter much of, the Beaufort Sea coast (Gavin 1976). Between the islands and the mainland there is a broad, shallow lagoon with a maximum water depth of approximately 9 m.

Because Cross Island is the outermost of the barrier islands, the lagoon (Stefansson Sound) is its widest (~18 km) in this vicinity. The ice within the barrier islands is typical undeformed fast ice (ice that remains fixed to the coast), which at the time of our study (April-May 1977) was approximately 1.8 m thick. Outside of the barrier islands the fast ice extends seaward for some distance. Our observations suggest that even the ice as far offshore as current meter Site C1 (see Fig. 2) is fast for most of the winter and early spring. Actually, in 1977 there were small 1- to 2-m-wide cracks that extended south to the north coast of Narwhal Island. Although these cracks opened and closed during our sampling period, they did not appear to result in ice motions that would produce crystal orientation changes of more than a few degrees, assuming that the preferred growth direction did not change during the same time period.

Sampling sites were selected based on three main considerations: first, we wished to obtain samples distributed over a broad area; second, we wanted to obtain samples around and in the channels between islands where the ocean current direction was reasonably well defined and at times different from what was anticipated as the general regional flow field; and finally, we had only limited helicopter support that we could devote to this project. The result is the distribution of sampling sites shown in Figure 2 (the site locations are marked by black dots). Most samples were obtained in the vicinity of the McClure Islands and specifically near Narwhal Island, three samples around Cross Island, four samples on a 60-km line down the main axis of Stefansson Sound, and two samples offshore of the barrier islands. The two offshore samples were collected during maintenance visits to our radar transponders and were acquired near transponder locations 4 and 6 [see Fig. 1 in Tucker et al. (1978)], the outermost of which was approximately 22 km offshore of the Cross Island-Narwhal Island axis. The sample sites near islands were located by measuring azimuths to known land points. The locations of the other sites were determined by the use of a precise VLF "On-Track" navigation system onboard the helicopter.

The sampling procedure at the majority of the sites studied was first to mark the direction of magnetic north on the sea ice surface, then to make vertical cuts with a chain saw until a rectangular block of ice with horizontal dimensions of approximately 30 × 30 cm was isolated. The height of the block was roughly 90 to 100 cm, limited by the length of the chain saw bar. The block was then broken at its base with an ice chisel and removed from the ice sheet with a pair of tongs. The ice below 1-m depth was sampled by obtaining a 7.8-cm-diameter core using a conventional CRREL corer. The difficulty with sampling by coring was that, although magnetic north was marked on the upper core surface, horizontal breaks invariably occurred across the core, causing loss of orientation. In most cases, however, the absolute orientation of the lower core segments could be regained exactly by matching irregularities in the breaks and lining up brine drainage channels and crystal features that extended across the break. In the few cases where orientation could not be maintained, a new core was drilled. The ice blocks and cores were then transported back to the Narwhal Island base camp where they were examined.

The majority of the structural studies were performed using thin sections. The ice was first cut into smaller blocks to isolate areas of interest. Next, slices of ice measuring 10 × 10 × 1 cm were cut from these blocks and frozen onto glass slides. The slides were then placed on a microtome and shaved down to thicknesses between 0.3 and 1.0 mm, depending on the mean diameter of the crystals in the ice.

The crystal orientation measurements were made on these thin sections using a large 3-axis universal stage specially designed for studying ice fabrics (a Rigsby stage). The determination of crystal orientation in sea ice is particularly easy in that ice from below the transition layer invariably has nearly horizontal c-axes and the trace of the (0001) plane in each crystal is clearly revealed by the alignment of brine pockets between the numerous platelets of pure ice that compose each of the crystals of sea ice [see Weeks and Assur (1967, 1969)]. Errors in determining the azimuth of each sample are estimated not to exceed ±3° in blocks and ±5° in cores. To obtain the data required to prepare each fabric diagram, crystal orientation measurements were usually made on three or four different thin sections from the same level

in the ice sheets. In addition, photographs were made of each thin section using a 10- × 12.5-cm view camera. These photographs also provide a permanent record of the texture, grain size, and substructure of the ice.

In some of the ice blocks, interesting gross structural features such as growth banding and pronounced brine drainage channels were noted. These were documented by cutting 1-cm-thick vertical ice slabs, placing the slabs on black cloth, and photographing them in reflected sunlight.

OBSERVATIONS

Figure 3 shows the orientations of individual c-axes as determined at six different sampling sites and plotted on a Schmidt equal-area projection via the lower hemisphere. Fairbairn (1949) and Langway (1958) discuss this type of presentation in detail. Briefly stated, a vertical c-axis plots in the center of the diagram, a horizontal c-axis plots on the outer circle at a location determined by its azimuth, and a c-axis that is dipping 20° to the N plots below N on the N-S line slightly less than 20% of the distance between N and the center of the diagram. The crystal orientations at all the sites studied were generally similar to those shown in Figure 3. *In all cases, the ice below the transition layer showed c-axis orientations that not only were within a few degrees of horizontal, but also exhibited striking preferred orientations within the horizontal plane.*

In calculating the mean of a given set of crystal orientations, it was first assumed that the deviations of the c-axes from perfectly horizontal were largely the result of our inability to cut the thin sections exactly in the horizontal plane. We believe this assumption to be essentially correct. If for the present the small remaining scatter is ignored, we can take each c-axis measurement to be represented by a point lying on the horizontal circle. We are, of course, dealing here with axial data insofar as the c-axis orientation of a crystal is not a vector and can equally well be represented by a point at either θ degrees or at $\theta + 180$ degrees (but not by both). Therefore, by a suitable rotation of the coordinate system, a given data set always can be made to occur within the range of (0°, 180°).

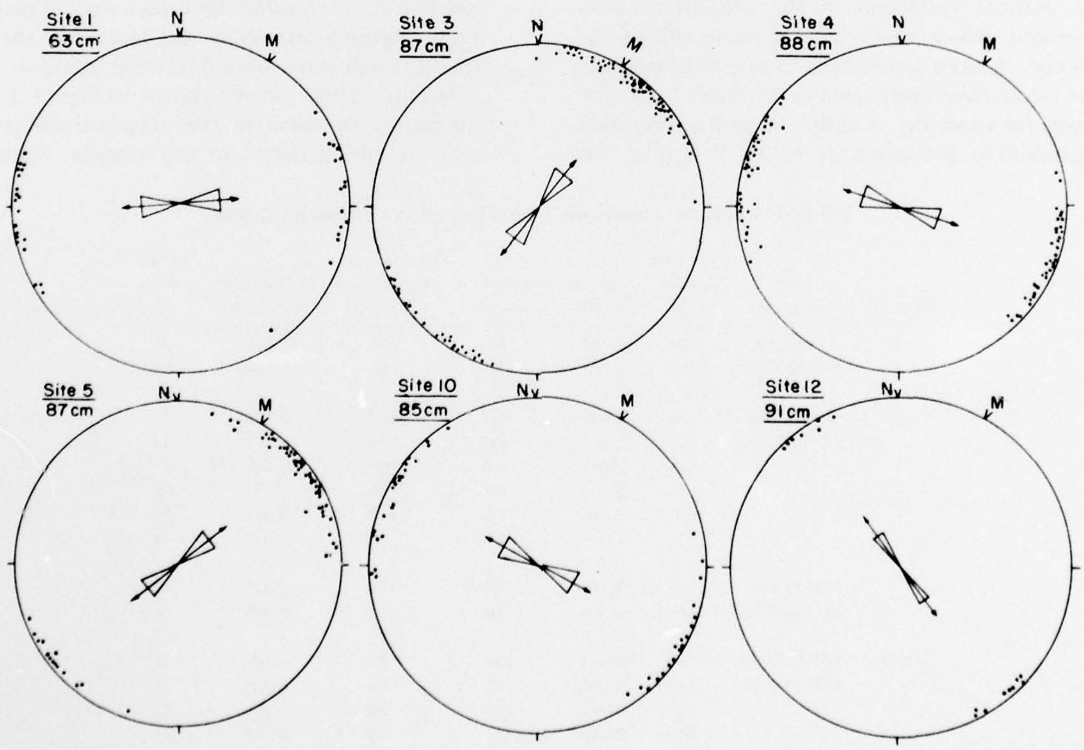


Figure 3. C-axis orientation plotted on a Schmidt net for six different sampling sites shown on Figure 2. The two-headed arrow indicates the circular mean $\bar{X}_0$ and the "bow-tie" indicates ± a standard deviation s_0.

The circular mean $\bar{X}_0$ and circular variance S_0 were then calculated by doubling the angles so that the data were distributed over 360°, and at the completion of the calculation transforming the data back to their original location. Mardia (1972) gives a detailed description of this procedure. It should be remembered that $0 \leq S_0 \leq 1$, with values near zero representing c-axis directions that are tightly clustered and values near 1 representing directions that are widely dispersed. We also present values of the standard deviation s_0 where $s_0 = [-2 \log_e (1 - S_0)]^{1/2}/2$ for values with a range of (0°, 180°). The range of s_0 is (0, ∞) and it can be considered somewhat analogous to the ordinary sample standard deviation on a line. In fact, because the data are so well clustered around the mean, the value of the linear standard deviation corresponds almost exactly to s_0. On each fabric diagram the mean orientation direction in the horizontal plane is indicated by a two-headed arrow and $\pm s_0$ by the outer bounds of the "bow-tie."

Vertical variations in crystal orientation

Before discussing regional orientation trends, the vertical variations in the preferred c-axis direction within the horizontal plane will be examined. If large differences in orientation direction occur over short vertical distances in the ice sheet, for example, if at 80-cm depth the c-axis alignment is N-S while at 90 cm it is E-W, we have a very different class of problem than if the orientation remains relatively constant once it becomes established.

Data bearing on this problem were collected from the ice that we studied in 1976 (Site N76) as well as in 1977 (Site 6). Table I presents a compilation of these results. The texture and c-axis fabrics at six different levels in the sea ice at Site 6 are shown in Figure 4. A similar presentation of the texture and fabric obtained from the ice at Site N76 can be found in Gow and Weeks (1977, their Fig. 3). Figure 5 is a plot of mean crystal orientation $\bar{X}_0$ and the standard deviation s_0 versus position in the ice sheet for these two sets of samples. $\bar{X}_0$ is clearly not constant, with rather large changes occurring at locations above 60-cm depth (20° at Site 6 and 24° at Site N76). Below 60-cm depth the variations are much less pronounced, amounting to 12° (Site 6) and 10° (Site N76). The suggestion of more nearly constant crystal orientations at locations below roughly 60 cm is also borne out by comparing the orientation found at Site 7 at 89 cm with that at 166 cm and the orientation found at Site 2 at 89 cm with that at 168 cm (Fig. 6). The differences in orientation are only 3 and 7° respectively. Figure 6 also shows the texture of the ice at Site 7 as shown in horizontal thin sections.

Another trend clearly shown in Figure 5 is a consistent decrease in the standard deviation with increasing depth of the sample. Figure 7

Table I. Vertical variations in preferred crystal orientation.

Site no.	*Site location*	*Depth to sample (cm)*	*Type of sample*	*No. of crystals in sample*	*$\bar{X}_0$, Avg c-axis orientation (° true)*	*S_0, Circular variance*	*s_0, Std dev (°)*
2	70°30.3′N	89	Block	51	76	0.051	19
	147°58.8′W	168	Core	20	83	0.024	13
6	70°25.1′N	15	Block	86	120	0.149	33
	147°39.3′W	30	Block	86	120	0.073	22
		60	Block	84	100	0.089	25
		90	Block	74	96	0.033	15
		139	Core	22	108	0.016	10
		177	Core	19	96	0.013	9
7	70°23.7′N	89	Block	70	119	0.023	12
	148°04.3′W	166	Core	16	122	0.005	6
N76	~70°23.9′N	8	Block	102	88	0.183	37
	147°31.0′W	14	Block	116	64	0.205	39
		26	Block	109	86	0.070	22
		66	Block	93	93	0.025	13
		95	Block	119	97	0.073	22
		156	Block	60	104	0.025	13
		183	Block	71	97	0.013	9

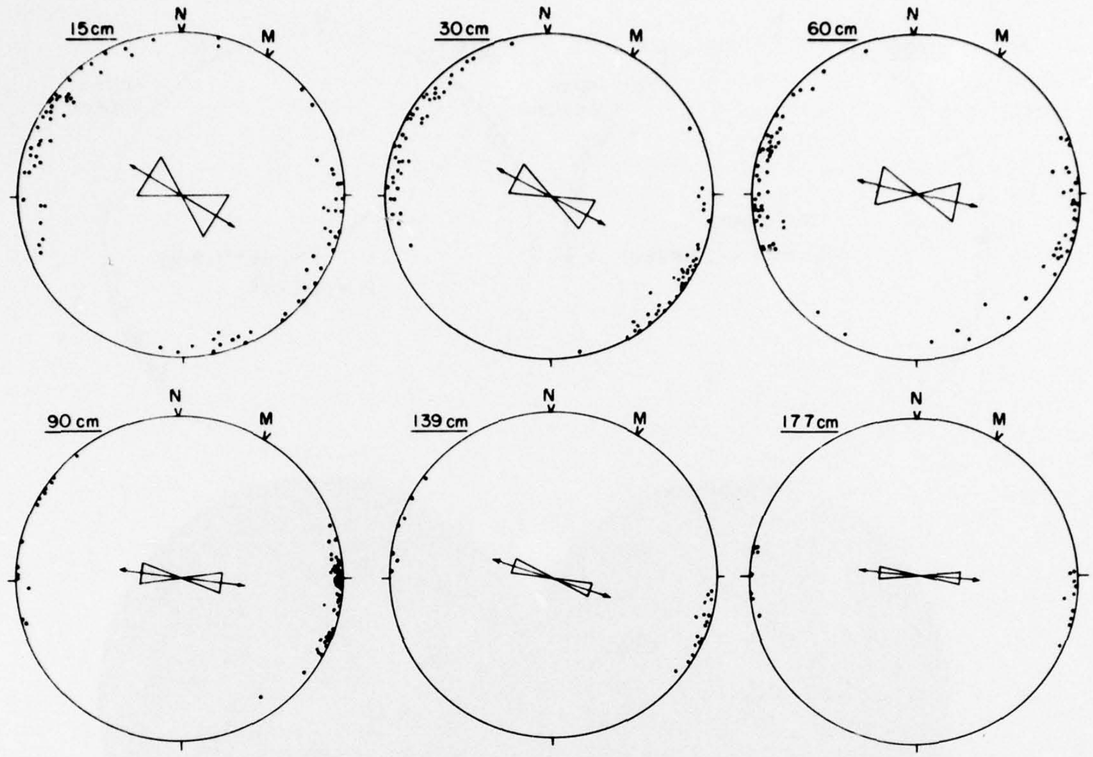


Figure 4. C-axis orientation obtained at six different depths in the ice sheet at Site 6. The two-head arrow indicates the circular mean $\overline{X}_0$ *and the "bow-tie" indicates* $\pm$ *a standard deviation* s_0.

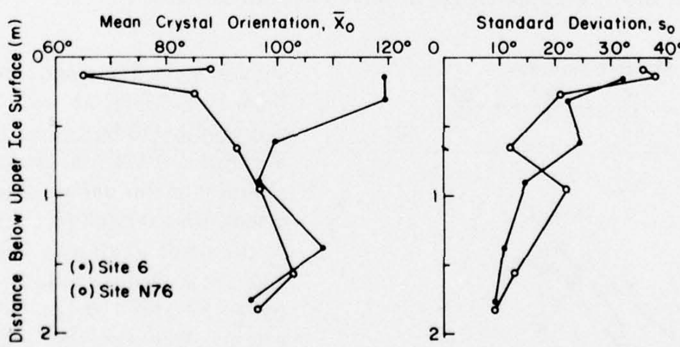


Figure 5. Mean crystal orientation in the horizontal plane $\overline{X}_0$ *and standard deviation* s_0 *as a function of vertical location in the ice sheet for Sites 6 and N76.*

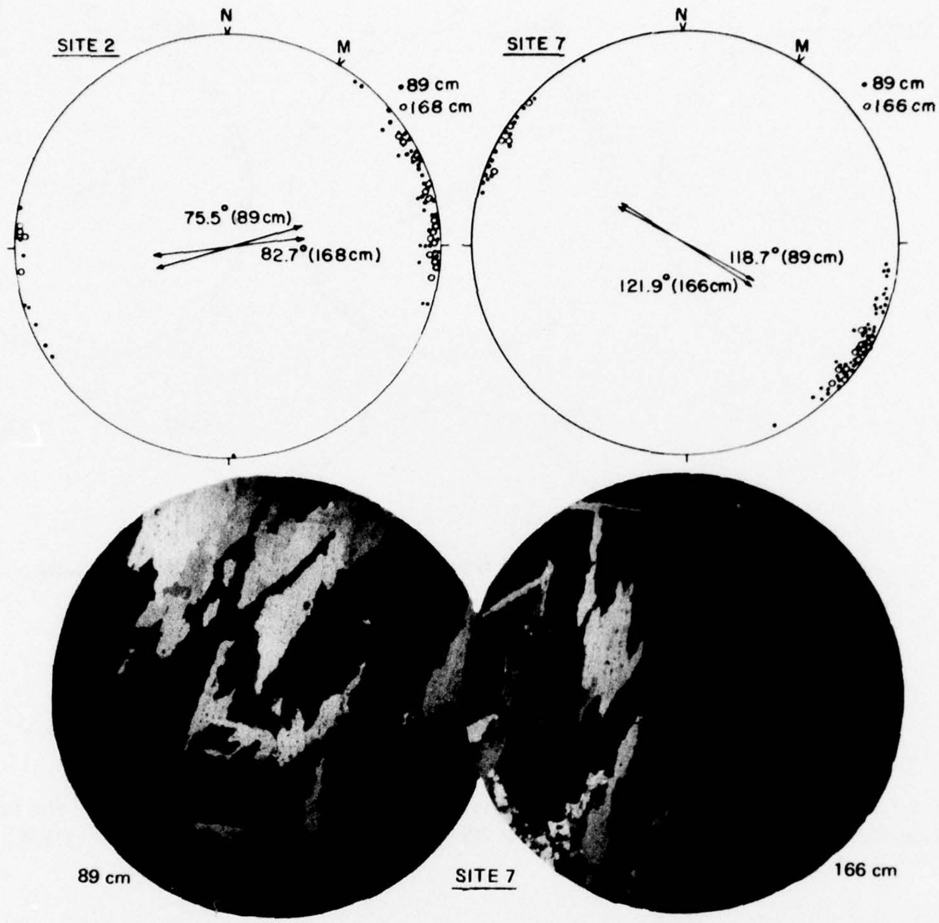


Figure 6. Schmidt net plots of individual c-axis orientations and the mean orientation at two different levels at Sites 2 and 7. Also shown are photomicrographs of thin-sections of ice from site 7. Photomicrographs taken at natural scale.

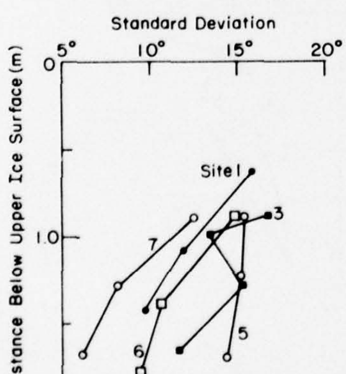


Figure 7. Standard deviation s_0 of the c-axis as measured in the horizontal plane as a function of vertical location in the ice sheet.

shows a similar trend illustrated by data collected at Site 6 as well as at four other less-thoroughly studied sites. The standard deviation at depths of 180-190 cm is 15° or less. In the remainder of this paper we will represent the c-axis orientation at each test site by a circular average $\bar{X}_0$ obtained at depths varying between 63 and 130 cm, with most values obtained at depths between 87 and 110 cm. This choice was a compromise between the larger number of crystals that could be studied on thin sections prepared from the bases of ice blocks and the lower scatter present in the lower levels in the ice sheet which could be sampled by coring. We ultimately decided against using the core data because in several cases there were uncertainties in our realignment of core segments that we broke in the process of sampling. Whatever the

drawbacks in the data set associated with the presence of the larger standard deviation occurring in the higher levels of the ice, the data set is, at least, reasonably homogeneous. We also believe that the changes in mean crystal orientation that occur below 60-cm depth, though small, are both significant and contain useful information. However at the present our vertical sampling is not adequate to delineate more than the presence of such changes.

Regional variations in crystal orientation

Narwhal and Cross Islands

A general map of the study area northeast of Prudhoe Bay, Alaska (Fig. 2), shows the location of each of the sample sites (indicated by black dots). The line through each dot indicates the mean direction of the c-axes in the horizontal plane. Table II gives a detailed statistical characterization of the crystal orientation at each sample site. In all cases, the crystal alignments were sufficiently striking in that the direction of preferred orientation could readily be estimated by visual examination of sea ice samples. In fact, at three sites $\bar{X}_0$ was estimated in this manner, including observations at Sites 18 and 19 and at Site P14 made by Martin and Kauffman (1977) on 20 March 1977, roughly a month before we began our studies.

Neglecting for a moment the observations made in the vicinity of Cross and Narwhal Islands, we see that the orientations in Figure 2 show two main features. Within the barrier islands the c-axes are oriented WNW-ESE, a direction that parallels the general trend of the coastline and the bottom contours in this vicinity (Sites 4, 6, 7, 9, 12 and P14). The ice within the barrier islands is by definition fast ice, with the maximum total motion over the growth season being approximately 100 m (Tucker et al. 1978). At sites outside the barrier islands (3 and 14), the orientation is quite different, trending NNE-SSW roughly normal to the coastline. As best we can tell, the ice at these two sites was also essentially fast from a time between soon after freezeup and 6 April 1977 (all pressure ridges were both several months old and composed of thin ice). However, on 6 April small motions were noted via our radar system and these motions continued at irregular intervals up until the time when we collected the ice samples. The maximum (x, y) motions observed were (156, 63) m for Site 3 and (440, 1198) m for Site 14 (Tucker et al. 1978). Here x is measured positive along the line starting at Cross Island and extending through the radar unit on Narwhal Island and y is taken as normal to x and positive out to sea. The motions were largely simple dilatation normal to the coast, produced by the opening of a number

Table II. Summary of crystal orientation information.

Site no.	*Site location*	*Depth to sample (cm)*	*Type of sample*	*No. of crystals in sample*	$\bar{X}_0$, *Avg c-axis orientation (° true)*	S_0, *Circular variance*	s_0, *Std dev (°)*
1	70°23.6′N, 147°30.7′W	63	Block	36	85	0.038	16
2	70°30.3′N, 147°58.8′W	89	Block	51	76	0.050	19
3	70°29.0′N, 147°31.7′W	87	Block	88	38	0.042	17
4	70°20.2′N, 147°36.5′W	88	Block	76	108	0.037	16
5	70°24.0′N, 147°31.0′W	87	Block	65	53	0.035	15
6	70°25.1′N, 147°39.3′W	90	Block	74	96	0.033	15
7	70°23.7′N, 148°04.3′W	89	Block	70	119	0.023	12
8	70°24.0′N, 147°30.6′W	94	Core	12	62	0.050	19
9	70°26.7′N, 148°29.3′W	102	Core	20	104	0.073	22
10	70°29.4′N, 147°55.4′W	85	Core	43	119	0.041	17
11	70°28.8′N, 147°54.6′W	85	Core	17	77	0.019	11
12	70°15.0′N, 147°00.0′W	91	Core	18	144	0.009	8
13	70°23.6′N, 147°29.9′W	60	Block	58	133	0.283	46
14	70°37.7′N, 147°29.7′W	≃100	Core	10	23	0.049	18
15	70°23.85′N, 147°32.4′W	80	Core	17	59	0.031	14
16	70°23.6′N, 147°28.4′W	79	Core	20	41	0.016	10
17	70°22.8′N, 147°26.1′W	108	Core	6	14	0.040	17
18	70°22.05′N, 147°29.5′W	110	Core		98		
19	70°22.65′N, 147°23.4′W	107	Core		78		
20*	71°20.3′N, 156°42.5′W	130	Core	33	33	0.014	10
P14†	70°18.8′N, 147°10.1′W	69	Core		105		

* Site in Chukchi Sea just offshore from Barrow, Alaska.
† Data provided by Martin and Kauffman (1977).

of small leads and cracks, and simple shear along these flaws parallel to the coast. We saw nothing to suggest that the ice might have rotated so as to make a significant change in c-axis orientation. In summary, although Site 3 and in particular Site 14 are not as "fast" as sites within the barrier islands, we believe that they can be considered as such for the purposes of the present study.

Figure 8 shows a detailed presentation of the crystal orientations observed in the vicinity of Cross Island. The c-axes generally follow the form of the island (Sites 2 and 10) except in the vicinity of passes between islands when the orientation is parallel to the pass (Site 11).

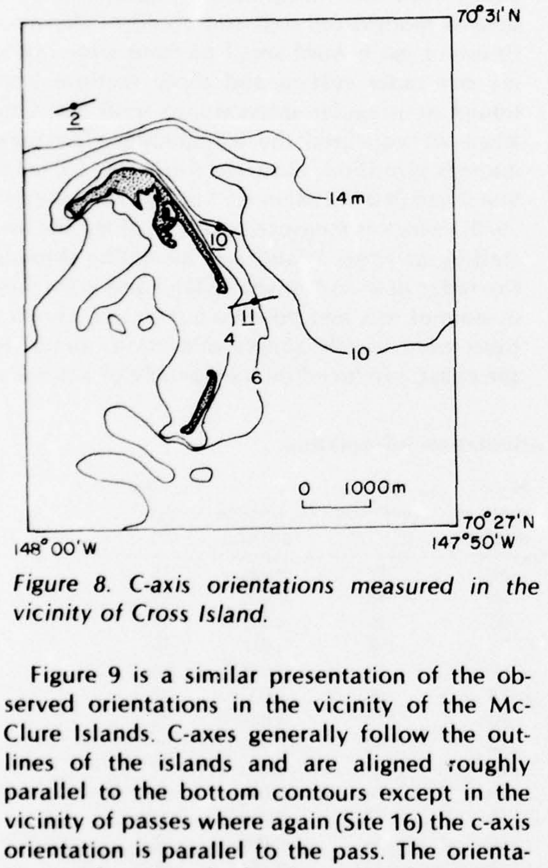


Figure 8. C-axis orientations measured in the vicinity of Cross Island.

Figure 9 is a similar presentation of the observed orientations in the vicinity of the McClure Islands. C-axes generally follow the outlines of the islands and are aligned roughly parallel to the bottom contours except in the vicinity of passes where again (Site 16) the c-axis orientation is parallel to the pass. The orientations at locations farther from the islands (Sites 18 and 19) are similar to those observed within Stefansson Sound. When Figure 9 is compared with the published maps of Narwhal Island, it will be noted that the island has changed form significantly (i.e., it has split into four separate islands) since 1955 when the maps were prepared (our map was based on an aerial photograph taken in the fall of 1975).

Barrow

Figure 10 shows fabric diagrams from two different levels (15 and 130 cm) at Site 20 in the near-shore fast ice along the Chukchi Sea coast at Barrow, Alaska. Even at the 15-cm level, there is a pronounced crystal orientation within the horizontal plane and at 130 cm the preferred orientation is as well developed (s_0 = 9.7°) as in the ice in the Beaufort Sea at depths of 1.8 m. The orientation direction is almost exactly the same at both levels with the c-axes aligned parallel to the coastline.

Kara Sea

Perhaps the most remarkable report of preferred c-axis alignments in sea ice is by Cherepanov (1971), who observed preferred crystal orientations in an area of the Kara Sea with lateral dimensions on the order of 1000 km. In fact, in the southern 600-km-long portion of this area, stretching along the coast of the Taimyr Peninsula, the crystal orientations were nearly constant. Figure 11 presents Cherepanov's data. Inasmuch as the exact coordinates of his sampling sites are not given, and latitude and longitude lines are not marked on his map, it was not possible to prepare Figure 11 as exactly as would be desired. Nevertheless, there is no doubt about the general patterns revealed by his observations. Cherepanov also does not describe the methods he used to determine the preferred orientation of the ice crystals; we would surmise that his methods were similar to ours.

Figure 11 shows that two principal c-axis directions were observed: a NE-SW orientation off the north coast of the Taimyr Peninsula and to the west of Severnaya Zemlya, and a NW-SE orientation further offshore to the north and to the west. Figure 11 also shows the boundary between the fast ice and the pack ice as marked by Cherepanov. It is clear that this boundary does not coincide with a change in the orientation of the c-axes at most places and that large areas designated as pack ice show similar orientations. We find this quite remarkable since the floes within a reasonably mobile ice pack would be expected to rotate as they drift under the influence of the winds and currents, a process which would presumably destroy a regional preferred orientation. We therefore expect that during the time when Cherepanov's observations were made (late March-early April 1969), and for some time prior to this, the majority of the ice in the Kara Sea was essentially fast, in that it showed little net drift or rotation. This is not

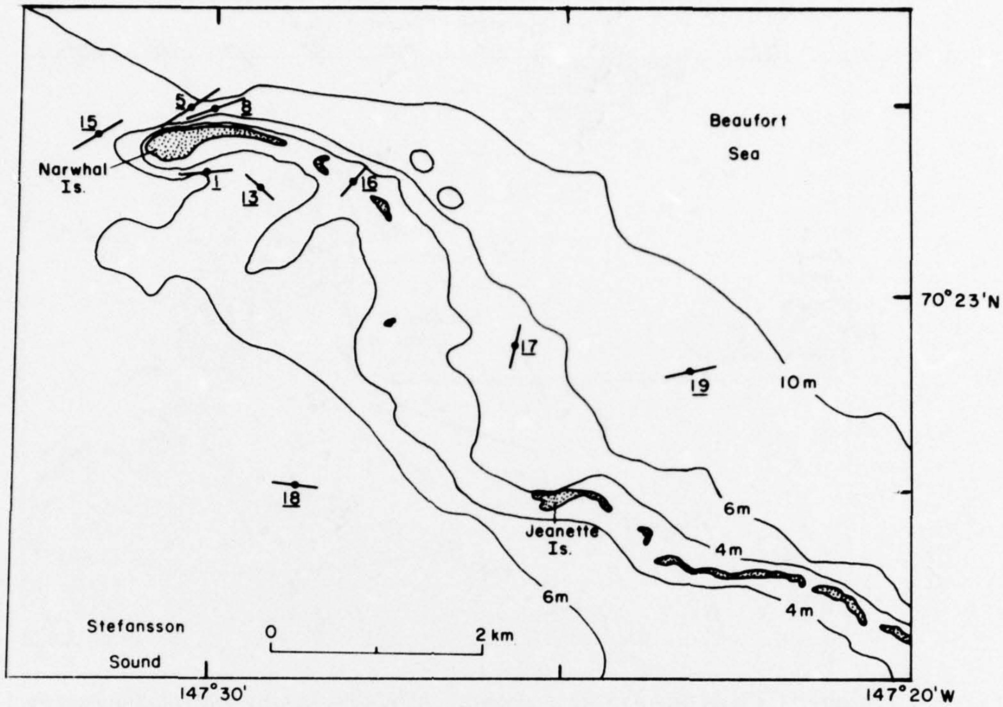


Figure 9. C-axis orientations measured in the vicinity of the McClure Islands.

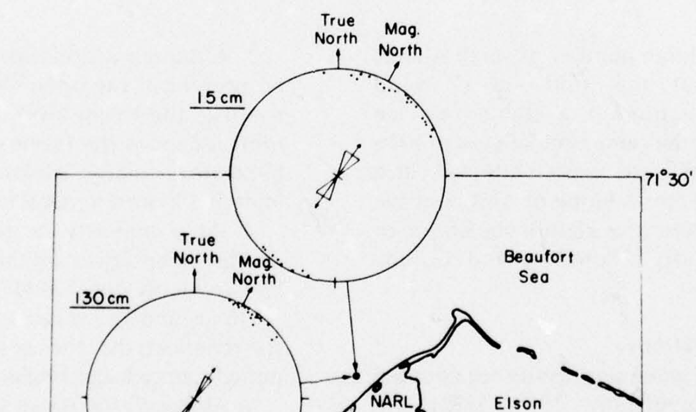


Figure 10. C-axis orientations measured at Site 20 offshore from Barrow, Alaska, in the Chukchi Sea.

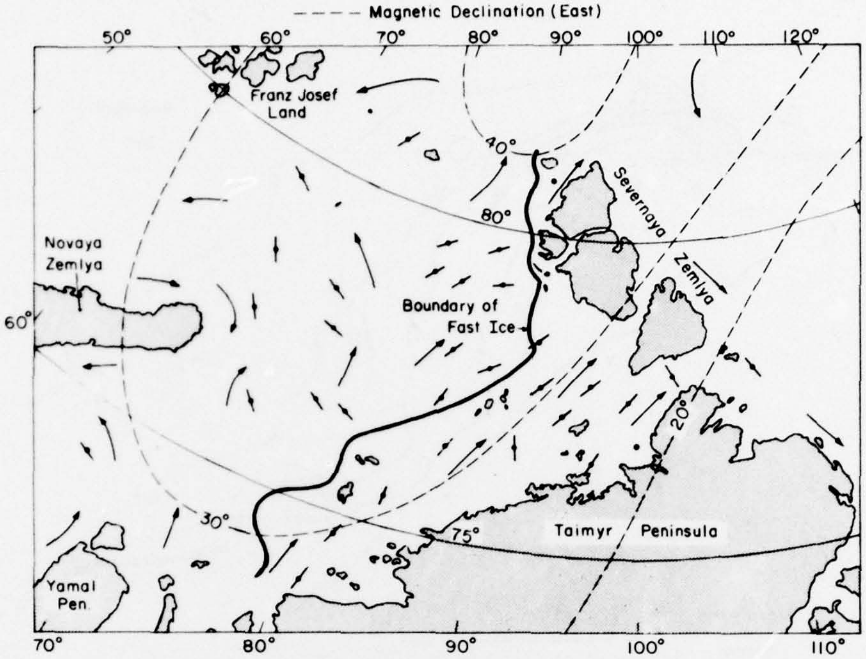


Figure 11. C-axis orientations as determined by Cherepanov (1971) in the Kara Sea region of the U.S.S.R. The arrows indicate estimated directions of the surface currents obtained from U.S. Navy sources.

unreasonable; the large number of small islands located throughout the study area would facilitate the formation of a stable fast ice cover. Also, during the same time of year in 1976 the AIDJEX stations were nearly stationary at a site 330 km off the North Slope of Alaska in the Beaufort Sea without the stabilizing effect of islands to the north (Thorndike and Colony 1978).

Summary of observations

We believe that, when our results are coupled with those of Cherepanov (1964, 1971) and Peyton (1966), several conclusions can be drawn about the nature of preferred crystal orientations in sea ice:

1. After sea ice has grown a few centimeters (~10 cm) via unidirectional columnar growth, a strongly developed c-axis horizontal crystal orientation develops and persists as long as the mode of growth remains unchanged.

2. At the great majority (95%) of the sites that have been studied, a strong preferred crystal orientation also develops within the horizontal plane.

3. Although a preferred c-axis direction may be present in the upper few centimeters of the ice (e.g., the 15-cm level off Barrow, Site 20), at most locations the fabric develops more slowly, becoming clearly evident only after approximately 50 cm of vertical ice growth.

4. At a majority of the sites sampled, the crystal orientation within the horizontal plane was so highly developed (standard deviations of <10° around the mean in the lower portion of the ice sheet) that the ice sheet as a whole would act as a very large single crystal.

5. Although the mean grain size as measured in the horizontal plane does commonly increase with depth in the upper part of the ice sheet, crystal sizes at the base of the ice are still quite small (2 to 3 cm). (The vertical dimensions of the crystals are quite large with some crystals extending completely through the columnar zone.)

6. The dimensions of regions where the sea ice crystals have similar orientations in the horizontal plane may be very large, extending for hundreds of kilometers.

7. At sites near the mainland the c-axis alignment is generally parallel to the coast.

8. At sites near islands the c-axis alignment generally follows the outline of the island.

9. In passes between islands, the c-axes are aligned parallel to the axis of the pass.

We believe that the existing evidence clearly suggests that strong c-axis alignments in the horizontal plane are typical for fast or near-fast ice along the margins of the Arctic Ocean. We would suggest that similar oriented ice will also be found in other areas, provided the ice grows thick enough for the preferred orientations to develop.

CAUSES

We know of no organized body of theory or observation within the extant crystal growth literature that suggests *a priori* that such striking c-axis alignments should develop on a regional basis in fast ice. Preferred orientations in metals equivalent to the c-axis horizontal orientations in sea ice are, of course, common (Tiller 1957, Hellawell and Herbert 1962, Flemings 1974); it is the preferred *alignment* in the horizontal plane that is unusual. Our observations on sea ice suggest why this is so. The c-axis alignments we observed develop slowly after a period of selective growth, implying that crystals in the favored alignment have only a slight advantage over less favored crystals. (This is in contrast to horizontal c-axis orientations which develop quickly as the result of a decided growth anisotropy.)

In crystal growth experiments carried out in the laboratory, the time scale is usually days or hours as contrasted to the scale of months for sea ice. Therefore, the strong crystallographic alignments within the growth plane may not have had sufficient time to develop. Also, as will be discussed, if our preferred explanation for these alignments is correct, conditions favoring such growth are usually absent during laboratory experiments. Since, we have shown that a strong c-axis alignment in sea ice is common; we will now try to piece together a physically plausible explanation for why this is so. This explanation can then be tested by laboratory experiments on the solidification of a variety of materials and, if verifiable, could possibly be utilized to develop techniques for producing oriented crystal aggregates for experimental and industrial purposes.

Only Cherepanov (1971) has speculated about the conditions causing the c-axis alignments, although he notes that sufficient data were not available to allow him to draw definite conclusions. The factors he discusses are the orienting influences of the initial ice skim, the earth's magnetic field, and the direction of the ocean currents beneath the ice. We will discuss these in sequence.

Initial ice skim

In principle, it is possible that the initial skim could all be composed of crystals with an aligned c-axis orientation in the horizontal plane. This alignment would then control the structure of the congelation ice that forms. The controlling factor might be the mechanical action of either wind or waves, or both, on the direction of free-floating ice nuclei. Cherepanov (1971) was unable to confirm this hypothesis, noting that it was difficult for him to believe that such steady weather conditions could prevail (over such large areas) during the formation of the primary ice layer. Our observations are in agreement with Cherepanov's. In particular we stress the observational fact that, although preferred orientations may be apparent in the upper portion of the ice sheet (see Figs. 4 and 10), the final average orientation at the bottom of a winter ice cover may differ quite appreciably from the initial average, and these changes can hardly be blamed on the crystal orientation in the initial ice skim. It is within the columnar zone, not within the initial ice skim, that the factors that govern the ultimate preferred orientation exert their control. It is our impression that the final orientation will be the same regardless of the orientation of the crystals in the initial skim. Of course, if there is an initial orientation that is favorably related to the final preferred orientation, the development of the final orientation may be facilitated.

Earth's magnetic field

Cherepanov (1971) suggests that the preferred crystal orientations may be caused by the influence of the earth's magnetic field, either directly or via a coupling with the potential difference that is known to be established between the solid and liquid phases during the freezing of salt solutions. Detailed descriptions are not provided as to how these couplings might work. We do not find his arguments to be compelling.

Although the structure of certain magnetically oriented sedimentary rocks may superficially resemble the structure of sea ice, there is little similarity in the physical processes controlling their formation. Also, the fact that a high electrical potential (≤200 V) can exist at the ice/solution interface during freezing (Hobbs 1974, p. 607-615) does not necessarily mean that there will be an interaction between the electrical and the magnetic fields that will cause aligned growth.

We base our rejection of the earth's magnetic field as an important factor in causing the crystal alignments on three types of arguments: theoretical, experimental, and observational. First, when the application of a magnetic field is found to have a significant effect on the alignment of a series of growing dendrites (Sahm 1971), the dendrites are composed of a ferromagnetic material (because of the magnetic field the dendrites are subjected to a turning moment that produces the preferred alignment). If ice does show ferromagnetic behavior (a point that is still highly debatable), it is only at temperatures significantly below those encountered naturally [<100K (Hobbs 1974)]. Therefore, there is no theoretical reason to anticipate that the crystal orientation of sea ice should be affected by a magnetic field.

Second, actual experiments on the effects of both magnetic and electrical fields on the structure of ice formed by unidirectional freezing of aqueous solutions of NaCl showed no measurable effect (Rohatgi et al. 1974), even though the applied magnetic field was over 80,000 times the anticipated earth's field (5 T as compared with 6×10^{-5} T). The only reservation we have about these experiments is that the total freezing time varied only from 3 to 15 minutes. Therefore, it is possible that an aligned structure did not have time to develop in spite of the large applied fields.

Third, whatever the mechanism, if the earth's magnetic field is the dominant factor, we would expect the preferred c-axis direction to have a constant orientation relative to the direction of the magnetic field. It is, of course, possible to see if this is so in both the Kara Sea and along the coasts of the Beaufort and Chukchi Seas. In the Kara Sea we have calculated the magnetic declinations at the time Cherepanov made his observations (March-April 1969) by using a 12th degree spherical harmonic expansion of the coefficients for the American World Chart model of the main geomagnetic field. The isodeclination lines are shown in Figure 11, indicating declinations varying from 20 to 40° to the east. Comparisons between these declinations and the observed c-axis orientations show that, although there is a reasonable correspondence at some locations, this appears to be fortuitous in that other locations show quite different relative orientations. A similar situation is found in the vicinity of Narwhal Island, where the magnetic declination is approximately 31°E; although the two offshore stations (Sites 3 and 14) show rough parallelism with the magnetic field, the near-shore crystal orientations are approximately normal to the field (Fig. 2). On the other hand, at Barrow (Fig. 10) the near-shore c-axis orientation is almost exactly parallel to the magnetic field.

To summarize, in a very rough way existing observations show that near-shore crystal orientations are parallel to the magnetic field lines along the coast of the Chukchi Sea off Barrow and along the coast of the Kara Sea north of the Taimyr Peninsula and are perpendicular to the field lines north of Prudhoe Bay. Further offshore the orientations are more nearly perpendicular to the field in the Kara Sea and parallel to the field north of Prudhoe Bay. In short, the geometric relations between the magnetic field and the crystal orientations, if any, are not simple and do not lead us to believe that they are of a "cause and effect" nature.

Currents

Cherepanov (1974) considered the possibility that the c-axis alignments that he observed were related to current directions. However, he rejected this possibility because he felt that currents could not "exert direct mechanical influence on the spatial arrangements of the fibrous structure of the ice, if they do not lead to a general disturbance of (the) fibrous growth of crystals." He also reportedly checked to see if c-axis alignment changed with sudden changes in current speed and direction and found that the (new) ice formed had a spatially arranged structure that was not related to the current direction. No details were provided concerning these observations.

Perhaps Cherepanov will be proven correct in rejecting a relationship between the direction of the current at the growing ice interface and the resulting c-axis alignment of the ice. However, we believe that such a relation is worthy of further consideration. We feel that the observations

we have presented here and in Gow and Weeks (1977) suggest that, contrary to Cherepanov's belief, direct mechanical influences causing a spatial rearrangement in the growing ice crystals are not essential to the development of strong preferred crystal alignments within the horizontal plane. We believe that such aligned aggregates develop by a process that is a natural extension of the mechanism that results in the c-axis horizontal orientation that is so characteristic of all but the uppermost layers of sea ice, i.e., by a process of selective crystal growth.

The question to be answered is, "Why, among a set of c-axis horizontal crystals growing at a given site, does a specific sub-set of crystals with their c-axes aligned in a favored direction have a growth advantage that allows them to gradually replace their less favorably oriented neighbors?" Here we stress that our observations indicate that the replacement is gradual, presumably utilizing crystals that exist at the interface as opposed to requiring the massive nucleation of new crystals oriented in the favored direction. We note, as did Cherepanov, that even in ice samples showing the strongest crystal alignments, there are invariably small crystals present that exhibit a variety of alternative orientations. It is possible that these crystals originate in the liquid ahead of the interface as the result of the convective transfer of cold brine from within the ice sheet downward into the underlying sea water. Once formed the small ice crystals would float upward attaching themselves in random orientations to the base of the ice sheet. [For a description of this process see Bennington (1967) and Martin (1974).] This means that, if there is a sudden change in the favored direction, there will not be an equally rapid change in the orientation of the ice, inasmuch as it would presumably take a sustained period of crystal growth before the newly favored orientation could "take over." Therefore, Cherepanov's observation that there was no relation between crystal orientation and sudden changes in current speed and direction does not necessarily rule out current as the controlling factor. If current is the factor, then there should be a systematic relation between the c-axis alignment and the time-averaged current speed and direction at the growing ice/water interface.

Kara Sea

We believe that Cherepanov's (1971) data can be reasonably interpreted in terms of what we know of the currents in the Kara Sea. The arrows in Figure 11 show the directions of the surface currents in the Kara Sea based on summaries presented by the U.S. Navy Hydrographic Office (1958) and the U.S. Naval Oceanographic Office (1970). It should be stressed that the data upon which these summaries are based are limited and that observations are presumably largely for the "ice-free" season. Even so, the agreement between the c-axis alignment and the current directions is surprisingly good if it is assumed that the crystals surviving at the bottom of the ice sheet are those that have their c-axes oriented parallel to the current.

There are two main currents in the Kara Sea. The first of these is a counterclockwise circulation in the western part of the sea, consisting of the Yamal Current which flows northward along the western side of the Yamal Peninsula until roughly 74 to 75°N latitude where it swings westward and joins the Novaya Zemlya Current which moves south along the south coast of Novaya Zemlya to complete the gyre. The c-axis orientations at 74°10'N, 67°00'E indicate the upper part of this circulation. The second main feature of the circulation of the Kara Sea is controlled by the outflow of the Ob and Yenisey Rivers, which mixes with sea water and moves northeastward toward Severnaya Zemlya from just east of the Yamal Peninsula. There are numerous locations where the c-axes are oriented parallel to this flow. In the central part of the Kara Sea (between 76° and 79°N and 75° and 81°E) there are several (four) c-axis measurements that are more westerly than the usually indicated current directions for the area. However, this is in an area where the currents are indicated as light. Also, it should be remembered that the current pattern under essentially fast ice where the wind has little if any effect does not have to coincide with currents as observed during the ice-free season. Certainly, current directions as indicated by the c-axis directions would be plausible for the area. Finally, it should be noted that the only c-axis site in the Laptev Sea indicates a southeasterly flow, in agreement with the known Severnaya Zemlya coastal flow which moves southerly off the east coast of Severnaya Zemlya and the Taimyr Peninsula.

There are, however, two sites that do not appear to fit the "c-axes parallel to the current" hypothesis. The first site, just northwest of the northernmost of the three main islands of Sever-

naya Zemlya, lacks a preferred orientation. We would expect a strong fabric there with the c-axes oriented SW-NE. The second site, located in the center of Boris Vilkitski Strait between the southernmost island of Severnaya Zemlya and the Taimyr Peninsula, has a c-axis orientation normal to the strait instead of parallel to it (the next site to the west at the entrance to the Strait does, however, have the "correct" c-axis orientation). We have no way of knowing if there are some unusual circumstances associated with Vilkitski Strait that make these observations reasonable within the framework of a "c-axis parallel to the flow direction" theory. Even considering these exceptions, we feel that the correlation between c-axis orientations and probable current directions in the Kara Sea area is sufficiently strong to be encouraging.

Narwhal and Cross Islands

The problem in comparing the crystal alignment information collected north of Prudhoe Bay, Alaska, with current measurements is similar to that encountered in the Kara Sea: there is a lack of pertinent current measurements with which comparisons can be made. This is particularly true in the winter when the sea is ice-covered. The locations of three current meter stations (C1, C2, C3) where long-term current observations were made are marked on Figure 2. Unfortunately, these stations were not operational in 1977 when our measurements were made. Stations C1 and C2 were located outside the barrier islands and were operated during the three-and-a-half weeks from 28 March to 22 April 1976, the same general time of year but a year earlier than our structural measurements. The meters, Aanderaa RCM-4's, were installed in the vicinity of our 1976 ice motion radar transponder stations R3 (C1) and R5 (C2) (Weeks et al. 1977) by Aagaard and Haugen (1977). Because of our radar observations we know that C2 did not move more than 20 m during the complete observation period and that C1 was also relatively motionless until 16 April when this ice became part of the pack ice. The meters were hung from the ice and were suspended 10 m below the lower ice surface in water greater than 30 m deep (C2) and 35 to 40 m deep (C1).

The records were not simple and are shown as progressive vector diagrams in Figure 12. At both meters velocities were generally small, with 20-minute mean values of 5 cm s^{-1} or less, and on a few locations (at Site C1 only) with values reaching as high as 10 cm s^{-1}.

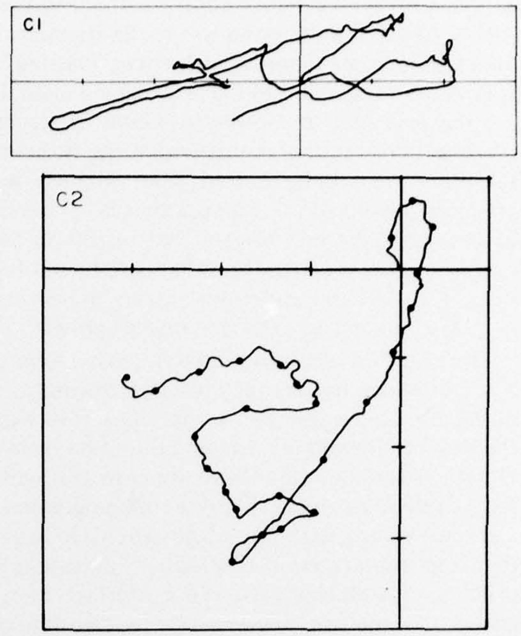


Figure 12. Progressive vector diagrams for the currents measured beneath the ice at Sites C1 and C2. The scale marks indicate 2 km and there is a time mark every 24 hours. The data are from the time period 28 March-22 April 1976.

The mean motions over the test period were very small, ¼ km/day or less, directed west-southwest (C1, 0.1 cm s^{-1} toward 240°T; C2, 0.3 cm s^{-1} toward 248°T). Tidal currents were on the order of 1 cm s^{-1}, with comparable energy in both the diurnal and semi-diurnal bands (Aagaard and Haugen 1977). We have no available wintertime current records for Stefansson Sound. Site C3 was operated over a 52-day period between late July and late September 1976 (Barnes et al. 1977) with the meter installed 1 m above the bottom in 5.5 m of water. The progressive vector diagram is also complex with a dominant trend of approximately 307°T pointing toward the NW exit from Stefansson Sound. The mean velocity was 13 cm s^{-1} and a peak velocity of 53 cm s^{-1} was recorded.

We are, of course, interested in the mean flow direction at the ice/water interface, which is not necessarily the flow direction at the depths of the current meters. Making a precise correction to obtain the flow direction at the ice/water interface is not a simple matter. Observations in the Beaufort Sea at deep water sites far from shore have indicated that the thickness of the

boundary layer under the ice is roughly 30 m (Hunkins 1974, McPhee and Smith 1975) and that a good average value for the turning angle in the Ekman spiral in the boundary layer is 24° to the right going down into the water (McPhee 1978). Even in deep water the correction from a 10-m current direction to the direction at the ice/water interface is not clear-cut in that some velocity profiles have indicated significant turning angles between the base of the ice and 10 m [16° (Hunkins 1974)] while other studies have not (McPhee and Smith 1975).

It must also be remembered that, because the total water depth at Sites C1 and C2 is approximately the thickness of the boundary layer and the spiral below the ice must join with the spiral from the bottom, this could result in an increased turning angle at 10 m. Whatever the turning angle is, it is doubtful that it would be larger than 24°. Therefore, on Figure 2 at each of the current meter sites we have indicated the 10-m current direction (solid arrow) as well as the direction of the current at the ice/water interface (dashed arrow), assuming a turning angle correction of 24°. The actual current direction at the ice/water interface will lie somewhere between these two values. At Site C3 the turning angle will probably be small because of the shallow water depth (5.5 m). Considering the nature of the data, the agreement between the measured flow directions and the observed ice crystal orientations is very good indeed. The crystal orientations show a SW-NE orientation offshore of the barrier islands similar to the observed flow, and a NW-SE orientation in Stefansson Sound which also parallels the observed flow and agrees with the belief (Barnes et al. 1977) that the currents within the sound should generally be oriented parallel to the isobaths, with a slight offshore component and a net NW drift.

The agreement between anticipated current directions and observed crystal orientations in the vicinity of Cross and the McClure Islands is also excellent. At Cross Island (Fig. 8) the c-axis alignments are such as to indicate flow around the streamlined northern coast of the island (Sites 2 and 10) and flow through the pass south of the main island (Site 11). In the McClure Islands (Fig. 9) the c-axis alignments also follow the expected streamlines that would be produced by west-southwesterly flow around Narwhal Island (Sites 1, 5, 8, 13, and 15). There are also alignments indicating flow parallel with the direction of the passes between islands (Sites 16 and 17), a southwesterly flow offshore of the islands (Site 19) and a westerly flow within Stefansson Sound (Site 18).

Barrow

Finally, the c-axis alignments we observed just off the Chukchi Sea coast at Barrow are oriented almost exactly parallel to the coast with a bearing of 33°T. This orientation is in excellent agreement with oceanographic observations, which indicate a strong northeasterly current parallel to the Chukchi Sea coast in the vicinity of Barrow (Continental Shelf Data Systems 1969, Hufford et al. 1977).

When the combined observations on the c-axis orientations in the sea ice from the Kara, Beaufort, and Chukchi Seas are compared with the anticipated current directions at the ice/water interface at these same locations, the agreement is excellent if it is assumed that the favored c-axis alignments are parallel to the direction of the current. Of the 54 different sites that were examined, only three appeared anomalous and these were all located in the Kara Sea: two sites showed no alignments where alignments might be expected, and one site showed an alignment almost 90° to the expected flow direction through Boris Vilkitski Strait. We do note, however, that it is very easy to make a 90° error in the several steps that go between removing a block or core from the ice and finally obtaining the mean crystal orientation.

Even considering these apparent exceptions to the "rule," we believe that *evidence clearly supports the working hypothesis that in sea ice the origin of the preferred c-axis alignments in the horizontal plane is primarily through a process of geometric selection, with the favored crystals being those with their c-axes most closely aligned parallel to the direction of the "long-term" current at the ice/water interface.*

Mechanisms

To understand how the current direction at the freezing interface controls the direction of the favored c-axis orientation, one must take a detailed look at the nature of the crystal growth process during the freezing of sea water. Sea ice does not grow with a microscopically smooth solid/liquid interface. Although detailed studies have never been made of the interface geometry during the formation of natural sea ice, casual field observations combined with the results of experiments on the freezing of salt solutions (Harrison and Tiller 1963a, b) show the ice/solu-

tion interface to be composed of a "forest" of dendritic plates with each plate elongated parallel to the basal plane. Figure 13 is a diagrammatic sketch of the situation. The macroscopic interface is defined by the plane specified by the tips of the dendrites. The inter-dendrite grooves, which are filled with brine, extend well behind the macroscopic interface (~2 cm) before there is sufficient ice-ice bonding between neighboring plates to give the ice mass an appreciable tensile strength. It is the entrapped brine between these plates that produces the characteristic arrays of brine pockets that are sea ice's "trademark." The cross-sectional profile of each individual plate is probably nearly parabolic, with the tip of the parabola pointing downward [cross sections are definitely nearly parabolic for individual dendritic plates growing into supercooled solutions (Hillig 1968)].

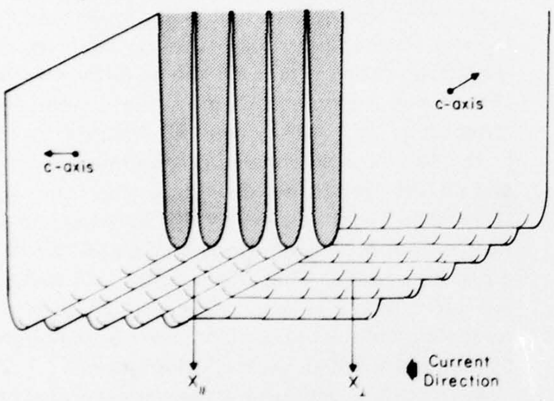


Figure 13. Sketch showing the interface geometry of two crystals of sea ice oriented so that the c-axis in one crystal (the left) is parallel to the current direction while in the other crystal (the right) the c-axis is oriented normal to it. $X_\perp$ and $X_\parallel$ indicate the locations of the schematic temperature and concentration profiles shown in Figure 14.

The formation of a stable dendritic interface during the growth of sea ice is the result of a process referred to as constitutional supercooling (Tiller et al. 1953, Rutter and Chalmers 1953). When ice forms from sea water, the rejection of salt by the ice causes a solute concentration maximum in the liquid next to the advancing solid/liquid interface with the impurity level falling off to the bulk salinity of the ambient liquid at a distance away from the interface. This solute profile, via the phase relations, determines the equilibrium freezing temperature of the liquid as a function of the distance ahead of the advancing macroscopic interface. If, as shown in Figure 14, certain temperature profiles occur in the liquid, a zone of constitutionally supercooled liquid (i.e., the supercooling is the result of the compositional profile) is produced ahead of the interface. As a result, a cellular or dendritic interface replaces a planar interface as the stable interface form. The problem is why does fluid flow normal to the planes of the protruding ice dendrites (i.e., flow parallel to the c-axis give a crystal a growth advantage relative to an identical crystal oriented so that flow is parallel to the ice dendrites. As best we know, it is only the orientation relative to the flow that causes this difference; in all other respects the two crystals are identical.

There are several ways that such grain competition mechanisms can operate (Harrison and Tiller 1963a):

1. An anisotropic grain boundary groove may allow one grain to expand at the expense of another for equilibrium contact angle reasons (Bolling and Tiller 1960).

2. An anisotropy in the effective thermal conductivity may be produced as the result of different interface morphologies causing favored grains to actually grow faster than their competitors.

3. The interface temperature of crystals in different orientations may be different, causing an interface step to form so that the leading grain can encroach upon its neighbors.

The first mechanism can only occur if the surface energy is a function of crystal orientation. There is some indication that anisotropic grain-boundary grooves may form between ice crystals when the basal plane is "exposed" at a grain boundary (Ketchum and Hobbs 1969). However, this cannot be important in the case we are considering as the basal planes are aligned parallel to the grain boundaries. Also, we would not expect the equilibrium contact angles to be affected by changes in the flow direction.

The other two mechanisms can occur in several different ways. In considering some of the possibilities, we will follow Harrison and Tiller (1963a) by discussing first the factors that control the conservation of heat at the macroscopic interface, then the factors that control its temperature. The equation for the conservation of heat at the macroscopic interface is

$$K_L \frac{dT_L}{dx} + v\Delta H = K_S \frac{dT_S}{dx} \qquad (1)$$

where K = thermal conductivity
T = temperature
v = freezing velocity
ΔH = latent heat of fusion

The subscripts S and L indicate solid and liquid respectively and the length coordinate x is oriented normal to the macroscopic interface as shown in Figure 13.

One possible effect producing an anisotropy in v would be an anisotropy in K_S. A mechanism for such an anisotropy is readily apparent in that the entrapment of brine between the plates of ice that compose a sea ice crystal results in a layered ice-brine aggregate with a much lower effective thermal conductivity parallel to the c-axis than perpendicular to it (Anderson 1958, Weeks 1958, Schwerdtfeger 1963). This is undoubtedly very important in favoring the dominance of c-axis horizontal crystals over c-axis vertical crystals at the base of the transition zone. However, we can see no reason why this effect should give crystals with their c-axes oriented parallel to the flow direction an advantage over horizontal c-axis crystals in other orientations. Other possible interactions mentioned by Harrison and Tiller (1963a) would be caused by the effect of changes in interface morphology on the temperature gradient in the liquid (dT_L/dx) and on the degree of chemical segregation (ΔH). We believe that these effects may not be important in our problem as there is no obvious change in interface morphology with c-axis orientation within the horizontal plane.

The interface temperature T_i can be expressed as follows

$$T_i = T_m + m\,C_i - (\gamma/\Delta S)\,K_i - (v/\mu_i) \qquad (2)$$

where
T_m = melting temperature of the pure material
m = liquidus slope for the solute
C_i = solute concentration at the interface
γ = solid/liquid interfacial energy
ΔS = entropy of fusion per unit volume
K_i = curvature of the main interface
μ_i = atomic kinetic coefficient for the freezing process.

Clearly there are a number of factors that can affect T_i if we were concerned with competitive growth between c-axis horizontally and vertically oriented crystals. However, because all our c-axes are horizontal and we are only concerned with growth parallel to the basal plane, we would expect γ and μ_i to be essentially constant. It should be mentioned here that recent experimental studies on the growth of ice den-

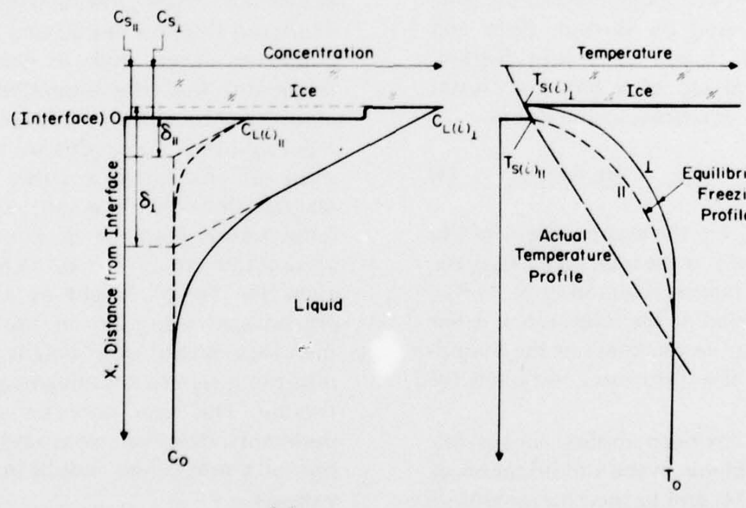


Figure 14. Schematic diagrams showing the assumed composition C and temperature T profiles associated with fluid flow parallel ∥ and perpendicular ⊥ to the c-axis. The subscripts L, s, and i indicate liquid, solid and interface respectively. The thickness of the diffusion limited boundary layer is given by δ. The step produced at the interface by the different values of $C_{L(i)\parallel}$ and $C_{L(i)\perp}$ is also shown.

drites in the basal plane, although in disagreement as to the best means of modeling the heat transfer between the growing dendrite and the surrounding water, agree that the rate of ice growth is governed only by the rate of removal of latent heat from the freezing interface (Fernandez and Barduhn 1967, Vlahakis and Barduhn 1974, Simpson et al. 1975). This is in contrast to the slower growth normal to the basal plane which appears to be controlled by a surface reaction involving 2-D nucleation or a screw dislocation mechanism.

We suggest that the mechanism most likely to produce the aligned crystals works through the control that the current direction has on the composition of the liquid at the dendrite tips and thus on the interface temperature. If the flow direction is parallel to the basal plates, then a stable boundary layer can build up along the dendrite tip. If, on the other hand, the flow is perpendicular to the plates, mixing will be enhanced at each plate tip and the thickness of the diffusion limited solute boundary layer δ will be reduced. Taking as a hypothesis that this occurs we can examine how much reduction in δ would be required to produce a significant "step" at the interface that could give a growth advantage to a crystal oriented with its basal planes normal to the flow direction. This question can be examined in a rough manner by using the relation developed by Burton, Prim and Slichter (BPS) (1953) to give the solute distribution in the liquid ahead of a growing crystal when convection is occurring in the liquid:

$$(C_{L(i)} - C_{S(i)})/(C_0 - C_{S(i)}) = \exp(v\delta/D_L) \qquad (3)$$

where $C_{L(i)}$ and $C_{S(i)}$ are the compositions of the liquid L and the solid S at the interface i, C_0 is the composition of the liquid (assumed to be 35 ‰) at a distance $\geq\delta$ ahead of the interface, v is the growth velocity, δ is the thickness of the boundary layer and D_L is the diffusion coefficient for salt in seawater.

The BPS relation has been applied successfully to numerous problems in the solidification of alloys (Flemings 1974) and to the entrapment of brine in sea ice (Weeks and Lofgren 1967, Cox and Weeks 1975). In the latter series of experiments, the ratio (δ/D_L) was determined to have the value 7.243×10^5 s m^{-1}. If $D_L \geq 7\times10^{-9}$ m^2 s^{-1} (Fofonoff 1962) then the thickness of δ could be taken as ~5 mm. We believe the actual value of δ to be less than 5 mm in that Terwilliger and Dizio (1970) have measured δ values of ~0.7 mm when salt solutions were frozen under conditions where convection does not occur. When convection does occur the values would be expected to be even smaller. Kvajić and Brajović (1970) suggest a value of 0.6 mm or less. This is in agreement with δ value estimates made for other systems in which convection occurs (Wilcox 1960, Sharp and Hellawell 1970).

In applying the BPS relation to a situation where the interface is cellular, there is also some question as to the appropriate value to use for $C_{S(i)}$. Because there is no bulk entrapment of salt at the cell tips we will assume that the equilibrium partition coefficient $k_0 \leq 10^{-4}$ (Harrison and Tiller 1963b), which for our purposes is equivalent to setting $C_{S(i)} = 0$. A rough estimate of v at the time we obtained our ice samples can be made by considering representative ice growth observations made in the Canadian Arctic (Bilello 1960) and the air temperatures in our study area; 20-cm ice growth in 30 days gives $v \sim 8\times10^{-8}$ m s^{-1}. Knowing v, D_L and C_0 we can then use the BPS equation to give the change in $(C_{L(i)} - C_0)$ as δ decreases. Under the growth conditions in which we are interested $(C_{L(i)} - C_0)$ decreases in a near-linear manner with δ from slightly over 2 ‰ at $\delta = 5$ mm to 0.04 ‰ at $\delta = 0.1$ mm. We can also estimate the "step" height between a crystal growing with its c-axis perpendicular to the flow and having a fully developed boundary layer and a neighboring crystal oriented so that flow is parallel to the c-axis and across the tips of the cellular plates resulting in a reduction in δ. To do this we need to know the slope of the liquidus curve from the phase diagram ($m \sim 0.054$°C g salt^{-1} kg brine^{-1}) and the temperature gradient in the ice sheet (~28° across 180 cm of ice or 15.6°C/m). Figure 15 gives the "step" height as a function of the percentage reduction in the boundary layer thickness. What "step" height is high enough to result in a significant advantage for the favored crystal? This can only be answered by experiments. However, we would guess that a fraction of a mm "step" would be a significant advantage.

Although the exact numbers we have presented are not important, we believe that Figure 15 suggests that small differences in δ, which presumably could result from different current directions relative to the orientation of the basal plates of the growing sea ice crystals, can give the favored orientation a definite

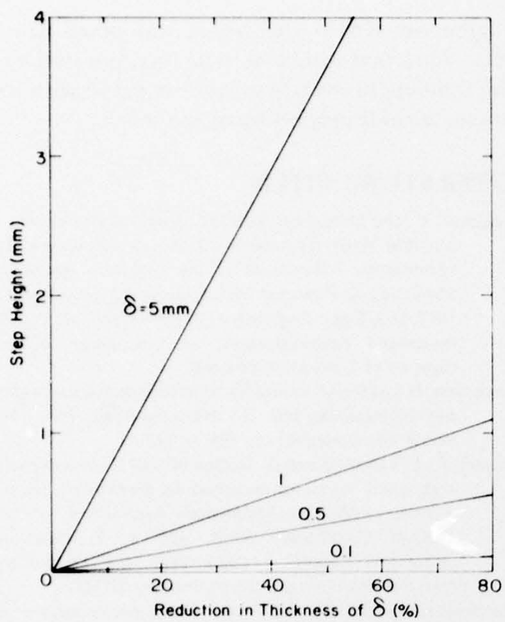


Figure 15. Step height at the growing interface resulting from different percentage reductions in the thickness of the diffusion limited boundary layer, δ. The different curves assume the fully developed boundary layer to have thicknesses of 0.1, 0.5, 1.0 and 5.0 mm as indicated.

growth advantage (step height) at the interface. If a crystal extends ahead of another it can grow laterally and expand its territory at the other crystal's expense. The orientation that is most favored (i.e., extends farthest into the liquid) is that with the c-axes parallel to the current direction at the interface. This result is, of course, in agreement with our field observations.

The flow of fluid against the upstream sides of the crystals that extend farthest into the melt would also result in the enhanced lateral growth of these crystals into the current inasmuch as the flow will wash the rejected salt preferentially away from the upstream sides of these dendrites. If this impinging liquid is constitutionally supercooled as the result of the impurity buildup ahead of the advancing interface, then the lateral growth of these favored crystals at the expense of other less favorably oriented crystals will be particularly enhanced (Miksch 1969).

CONCLUSIONS AND CONSEQUENCES

In this paper it has been shown that the fast (or near fast) ice along the Alaskan coast of the Beaufort and Chukchi Seas and in the Kara Sea off the U.S.S.R. is composed of crystals having striking preferred alignments within the horizontal plane. These alignments develop through a process of geometric selection in which crystals in the favored orientation eliminate cystals with less favored orientations by growing laterally and cutting them off from the melt. Although preferred crystal alignments may be present in the upper few centimeters of a sheet of sea ice, alignments gradually become better defined toward the bottom of the ice sheet. The patterns of the crystal alignments around islands and in passes between islands and the good agreement between alignments and the few long-term current measurements that are available suggest that the preferred orientations have their c-axes aligned parallel to the direction of the current at the interface. This correlation is discussed in terms of grain competition mechanisms in general and is believed to be the result of changes in the thickness of the diffusion-limited boundary layer with changes in the flow direction across the interface (when flow is normal to the planes of the tips of the protruding cells, mixing is enhanced and the boundary layer thickness is minimized). This, in turn, causes less buildup of solute at such interfaces and allows them to grow slightly ahead of their less favorably oriented neighbors. In addition, the movement of supercooled liquid along the interface favors enhanced lateral growth of the advanced crystals. The result is an ice mass composed of columnar crystals that have their c-axes aligned parallel to the mean flow direction.

There are a number of important consequences that would appear to follow from these observations:

1. Crystal alignment should occur at any site where there are significant currents, provided the ice grows thick enough for the alignment to develop. Therefore, we would expect such alignments to be typical at most fast ice locations. It is also quite possible that alignments will form even in pack ice areas such as the Beaufort or Kara Seas provided the ice motions during the winter are small.

2. Crystal alignment can be used to map current patterns in fast ice areas. For instance, Cherepanov's (1971) crystal alignments probably provide the best available data on current directions under the ice in the Kara Sea. The use of such alignments could be very valuable in oceanographic reconnaissance studies of the Canadian Archipelago where current information is, at present, both extremely limited and

difficult to obtain because of the nearly continuous ice cover. However, at present supplementary current measurements or model calculations would have to be used to obtain directions and speeds of the currents.

3. The preferred orientations are so pronounced that the sea ice should act as a giant single crystal even though the actual grain sizes are only a few centimeters. This has a number of important consequences.

a. Assuming generally long-shore currents near a coast, the resulting fabric will cause the ice to have its direction of maximum tensile strength oriented normal to the coast.

b. The hard-fail compressive strength of such oriented ice would be approximately three times the easy-fail compressive strength (Peyton 1966). (This would undoubtedly have to be considered in any design calculations in which the compressive strength of fast ice was important.)

c. The orientations would cause effects related to the thermal expansion and contraction of the ice to be directionally dependent.

d. The directional dependence of both the strength of the radar return from sea ice (Campbell and Orange 1974) and the effective DC resistivity (Kohnen 1976) is undoubtedly, as suggested by these authors, caused by the aligned crystal orientations. (It should, therefore, be possible to use such techniques to indirectly determine the degree of crystal alignment.)

4. There is some indication (Martin 1977) that aligned ice is capable of entrapping more spilt crude oil than non-aligned ice. Although it is not presently apparent to us why this should be the case, if this result can be verified, it may prove to be important in designing oil clean-up procedures for ice-covered areas.

5. The knowledge that fluid flow exerts such a strong effect on crystal orientation may well prove useful in laboratory studies of the solidification of other materials and in the design of solidification procedures for industrial uses.

To verify and clarify the explanations and queries raised in this paper will take additional field measurements. We plan to start these studies by undertaking observations along the Alaskan Arctic coast between Barter Island and Kotzebue during the late winter of 1978. There is also a need for a more realistic theoretical analysis of possible processes that could contribute to the alignment as well as complementary experimental studies. Whatever the cause we feel that there is little doubt that strong c-axis alignments within the horizontal plane are a fact-of-life that will have to be incorporated into the thinking of investigators concerned with the processes and properties of sea ice.

LITERATURE CITED

Aagaard, K. and D. Haugen (1977) Current measurements in possible dispersal regions of the Beaufort Sea. *Environmental Assessment of the Alaskan Continental Shelf*, vol. 4, Principal Investigators Reports, Jan-Mar 1977, U.S. Dept. Commerce (National Oceanic and Atmospheric Administration) — U.S. Dept. Interior (Bureau of Land Management).

Anderson, D.L. (1958) A model for determining sea ice properties. In *Arctic Sea Ice*. U.S. National Acad. Sci. — National Res. Council Pub. 598, p. 148-52.

Barnes, P., E. Reimnitz and D. McDowell (1977) Current meter and water level observations in Stefansson Sound, summer 1976. *Environmental Assessment of the Alaskan Continental Shelf*, vol. 4, Principal Investigators Reports, Jan-Mar 1977, U.S. Dept. Commerce (NOAA) — U.S. Dept. Interior (BLM).

Bennington, K.O. (1967) Desalination features in natural sea ice. *J. Glaciol.*, vol. 6, no. 48, p. 845-57.

Bilello, M.A. (1960) Formation, growth, and decay of sea ice in the Canadian arctic archipelago. Snow, Ice and Permafrost Research Establishment (SIPRE) Research Report 65. AD 653137.

Bolling, G.F. and W.A. Tiller (1960) Growth from the melt. I. Influence of surface intersections in pure metals. *J. Appl. Phys.*, vol. 31, p. 1345-50.

Burton, J.A., R.C. Prim and W.P. Slichter (1953) The distribution of solute in crystals grown from the melt. Part I, I. Theoretical, *J. Chem. Phys.*, vol. 21, no. 11, p. 1987-91.

Campbell, K.J. and A.S. Orange (1974) The electrical anisotropy of sea ice in the horizontal plane. *J. Geophys. Res.*, vol. 79, no. 33, p. 5059-63.

Cherepanov, N.V. (1964) Structure of sea ice of great thickness (in Russian). *Trudy Arkt. i Antarkt. Nauchno-Issled. Instit.*, vol. 267, p. 13-18.

Cherepanov, N.V. (1971) Spatial arrangement of sea ice crystal structure (in Russian). *Problemy Arktiki i Antarktiki*, vol. 38, p. 137-40.

Continental Shelf Data Systems (1969) *Beaufort Sea-Arctic Coast: Oceanographic and Climatologic Data*, vol. 1, Continental Shelf Data Systems, Rockville, Maryland.

Cox, G.F.N. and W.F. Weeks (1975) Brine drainage and initial salt entrapment in sodium chloride ice. U.S. Army Cold Regions Research and Engineering Laboratory Research Report 345. AD-A021765.

Fairbairn, H.W. (1949) *Structural petrology of deformed rocks*. Cambridge, Mass.: Addison-Wesley Press, 344 p.

Fernandez, R., and A.J. Barduhn (1967) The growth rate of ice crystals. *Desalination*, vol. 3, p. 300-42.

Flemings, M.C. (1974) *Solidification processing*. New York: McGraw-Hill.

Fofonoff, N.P. (1962) Physical properties of sea water. In *The Sea* (M.N. Hill, ed.), vol. 1. New York: Interscience, p 3-30.

Gavin, A. (1976) Wildlife of the North Slope: The islands offshore Prudhoe Bay, the snow geese of Howe Island, The seventh year of study, The Public Relations Department of the Atlantic Richfield Company, Los Angeles, 70 p.

Gow, A.J. and W.F. Weeks (1977) The internal structure of fast ice near Narwhal Island, Beaufort Sea, Alaska. CRREL Report 77-29, 8 p. AD-A030413.

Harrison, J.D. and W.A. Tiller (1963a) Ice interface morphology and texture developed during freezing. *J. Appl. Phys.*, vol. 34, p. 3349-55.

Harrison, J.D., and W.A. Tiller (1963b) Controlled freezing of water. In *Ice and Snow, Properties, Processes, and Applications*, (W.D. Kingery, ed.) Cambridge: M.I.T. Press, p. 215-25.

Hellawell, A., and P.M. Herbert (1962) The development of preferred orientations during the freezing of metals and alloys. *Proc. Roy. Soc.*, vol. A 269, p. 560-73.

Hillig, W.B. (1968) The solution of the dendrite problem for the edgewise growth of a platelet. *J. Crystal Growth*, vol. 3, no. 4, p. 611-20.

Hobbs, P.V. (1974) *Ice physics*. Oxford: Clarendon Press.

Hufford, G. et al. (1977) Physical oceanography. In *Beaufort Sea Synthesis Report, Spec. Bull. 15*, Outer Continental Shelf Environmental Assessment Program, Arctic Project Office, Geophysical Institute, University of Alaska, p. 29-42.

Hunkins, K. (1974) The oceanic boundary layer and ice-water stress during AIDJEX 1972. *AIDJEX Bulletin no. 26*, p. 109-127.

Ketchum, W.M., and P.V. Hobbs (1969) An experimental determination of the surface energies of ice. *Phil. Mag.*, vol.19 p. 1161-73.

Kohnen, H. (1976) On the DC-resistivity of sea ice. *Z. für Gletscherkunde und Glazialgeologie*, vol. 11, no. 2, p. 143-54.

Kvajić, G. and V. Brajović (1970) Segregation of (^{134}Cs)$^+$ impurity during growth of polycrystalline ice. *Canad. J. Phys.*, vol. 48, no. 23, p. 2877-87.

Kvajić, G., V. Brajović, M. Milosevic-Kvajić and E.R. Pounder (1973) Selective growth of ice crystals from dilute water solution. In *Physics and Chemistry of Ice* (E. Whalley et al., eds.). Royal Soc. Canada, Ottawa, p. 251-55.

Langway, C.C. (1958) Ice fabrics and the universal stage. SIPRE Technical Report 62. AD 206681.

Mardia, K.V. (1972) *Statistics of directional data*. New York: Academic Press.

Martin, S. (1974) Ice stalactites: Comparison of a laminar flow theory with experiment. *J. Fluid Mech.*, vol. 63, no. 1, p. 59-79.

Martin, S. (1977) The seasonal variation of oil entrainment in first year arctic sea ice: A comparison of NORCOR/OCS observations. Univ. of Washington, Dept. of Oceanog. Special Report no. 71.

Martin, S., and P. Kauffman (1977) Data report on the March 1977 field traverse of BLM/NOAA Task Order Contract No. 03-5-022-67, Task Order No. 6, R.U. no. 87, University of Washington Dept. Oceanog. Special Report, 30 June.

McPhee, M.G. (1978) An analysis of pack-ice drift in summer. Internat. Comm. Snow and Ice/Arctic Ice Dynamics Joint Exp. Sympos. on Sea Ice Processes and Models, University of Washington Press, Seattle.

McPhee, M.G., and J.D. Smith (1975) Measurements of the turbulent boundary layer under pack ice. *AIDJEX Bulletin no. 29*, p. 49-92.

Miksch, E.S. (1969) Solidification of ice dendrites in flowing supercooled water. *Trans. Metal. Soc. AIME*, vol. 245, p. 2069-72.

Perey, F.G.L., and E.R. Pounder (1958) Crystal orientation in ice sheets. *Canad. J. Phys.*, vol. 36, p. 494-502.

Peyton, H.R. (1966) Sea ice strength. University of Alaska Final Report, Office of Naval Research Contract NONR-2601(01), 285 p.

Rohatgi, P.K., S.M. Jain and C.M. Adams, Jr. (1974) Effect of magnetic and electrical fields on dendritic freezing of aqueous solutions of sodium chloride. *Materials Sci. Eng.*, vol. 15, p. 283-90.

Rutter, J.W., and B. Chalmers (1953) A prismatic substructure formed during solidification of metals. *Canad. J. Phys.*, vol. 31, p. 15-39.

Sahm, P.R. (1971) Directional growth of Bi-Co alloys in a magnetic field. *J. Cryst. Growth*, vol. 8, p. 109-16.

Schwerdtfeger, P. (1963) The thermal properties of sea ice. *J. Glaciol.*, vol. 4, no. 36, p. 789-807.

Sharp, R.M., and A. Hellawell (1970) Solute distributions at non-planar, solid-liquid growth fronts, III. With convective mixing in the liquid, *J. Crystal Growth*, vol. 8, p. 29-32.

Simpson, H.C., G.C. Beggs and J. Deans (1975) New theories of the a-axis growth of ice crystals. *Int. J. Heat Mass Transfer*, vol. 18, p. 615-22.

Smith, D.D. (1964) Ice lithologies and structures of ice island Arlis II. *J. Glaciol.*, vol. 5, no. 37, p. 17-38.

Tabata, T., and N. Ono (1962) On the crystallographic study of several kinds of ices (in Japanese). *Low Temperature Science*, vol. A20, p. 199-214.

Terwilliger, J.P., and S.F. Dizio (1970) Salt rejection phenomena in the freezing of saline solutions. *Chem. Eng. Sci.*, vol. 25, p. 1331-49.

Thorndike, A.S., and R. Colony (1978) Large-scale ice motion in the Beaufort Sea during AIDJEX, April 1975-April 1976. Internat. Comm. Snow and Ice/ Arctic Ice Dynamics Joint Exp. (AIDJEX) Symposium on Sea Ice Processes and Models, University of Washington Press, Seattle.

Tiller, W.A. (1957) Preferred growth direction. *Trans. AIME (J. Metals)*, vol. 209, p. 847-56.

Tiller, W.A., K.A. Jackson, J.W. Rutter and B. Chalmers (1953) The redistribution of solute atoms during the solidification of metals. *Acta Metallurgica*, vol 1, p. 428-37.

Miksch, E.S. (1969) Solidification of ice dendrites in flowing supercooled water. *Trans. Metal. Soc. AIME*, vol. 245, p. 2069-72.

Perey, F.G.L., and E.R. Pounder (1958) Crystal orientation in ice sheets. *Canad. J. Phys.*, vol. 36, p. 494-502.

Peyton, H.R. (1966) Sea ice strength. University of Alaska Final Report, Office of Naval Research Contract NONR-2601(01), 285 p.

Rohatgi, P.K., S.M. Jain and C.M. Adams, Jr. (1974) Effect of magnetic and electrical fields on dendritic freezing of aqueous solutions of sodium chloride. *Materials Sci. Eng.*, vol. 15, p. 283-90.

Rutter, J.W., and B. Chalmers (1953) A prismatic substructure formed during solidification of metals. *Canad. J. Phys.*, vol. 31, p. 15-39.

Sahm, P.R. (1971) Directional growth of Bi-Co alloys in a magnetic field. *J. Cryst. Growth*, vol. 8, p. 109-16.

Schwerdtfeger, P. (1963) The thermal properties of sea ice. *J. Glaciol.*, vol. 4, no. 36, p. 789-807.

Sharp, R.M., and A. Hellawell (1970) Solute distributions at non-planar, solid-liquid growth fronts, III. With convective mixing in the liquid, *J. Crystal Growth* vol. 8, p. 29-32.

Simpson, H.C., G.C. Beggs and J. Deans (1975) New theories of the a-axis growth of ice crystals. *Int. J. Heat Mass Transfer*, vol. 18, p. 615-22.

Smith, D.D. (1964) Ice lithologies and structures of ice island Arlis II. *J. Glaciol.*, vol. 5, no. 37, p. 17-38.

Tabata, T., and N. Ono (1962) On the crystallographic study of several kinds of ices (in Japanese). *Low Temperature Science*, vol. A20, p. 199-214.

Terwilliger, J.P., and S.F. Dizio (1970) Salt rejection phenomena in the freezing of saline solutions. *Chem. Eng. Sci.*, vol. 25, p. 1331-49.

Thorndike, A.S., and R. Colony (1978) Large-scale ice motion in the Beaufort Sea during AIDJEX, April 1975-April 1976. Internat. Comm. Snow and Ice/ Arctic Ice Dynamics Joint Exp. (AIDJEX) Symposium on Sea Ice Processes and Models, University of Washington Press, Seattle.

Tiller, W.A. (1957) Preferred growth direction. *Trans. AIME (J. Metals)*, vol. 209, p. 847-56.

Tiller, W.A., K.A. Jackson, J.W. Rutter and B. Chalmers (1953) The redistribution of solute atoms during the solidification of metals. *Acta Metallurgica*, vol 1, p. 428-37.

Tucker, W.B., W.F. Weeks, A. Kovacs and A.J. Gow (1978) Nearshore ice motion at Prudhoe Bay, Alaska, Internat. Comm. Snow and Ice/Arctic Ice Dynamics Joint Exp. (AIDJEX) Sympos. on Sea Ice Processes and Models, University of Washington Press, Seattle.

U.S. Naval Oceanographic Office (1970) Major currents along the coasts of Norway and the USSR to the Kurils, Naval Oceanographic Office Tech. Rept. TR-222, Washington, D.C.

U.S. Navy Hydrographic Office (1958) *Oceanographic Atlas of the Polar Seas, Part II Arctic*, U.S. Navy Hydrographic Office H.O. Pub. No. 705, Washington, D.C.

Vlahakis, J.G., and A.J. Barduhn (1954) Growth rate of an ice crystal in flowing water and salt solutions. *Amer. Inst. Chem. Eng. J.*, vol. 20, p. 581-91.

Weeks, W.F. (1958) The structure of sea ice: A progress report. In *Arctic Sea Ice*, U.S. National Acad. Sci. - National Res. Council Pub. 598, p. 96-99.

Weeks, W.F. and A. Assur (1967) The mechanical properties of sea ice. *CRREL Science and Engineering Monograph* II-C3, 80 p. AD 662716.

Weeks, W.F. and A. Assur (1969) The fracture of lake and sea ice. CRREL Research Report 269. AD 697750.

Weeks, W.F. and W.L. Hamilton (1962) Petrographic characteristics of young sea ice, Point Barrow, Alaska. *Am. Mineralog.*, vol. 47, p. 945-61.

Weeks, W.F. and G.Lofgren (1967) The effective solute distribution coefficient during the freezing of NaCl solutions. In *Physics of Snow and Ice, Proceed. Internat. Conf. on Low Temp. Sci.* (H. Oura, ed.). Inst. of Low Temp. Sci., Hokkaido University, Sapporo, vol. I, Part 1, p. 579-597.

Weeks, W.F., A. Kovacs, S.J. Mock, W.B. Tucker, W.D. Hibler and A.J. Gow (1977) Studies of the movement of coastal sea ice near Prudhoe Bay, Alaska, U.S.A. *J. Glaciol.*, vol. 19 no. 81, p. 533-545.

Wilcox, W.R. (1960) Fractional crystallization from melts. Lawrence Rad. Lab., Berkeley, Rept. UCRL — 9213.

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Weeks, W.F.

Preferred crystal orientations in the fast ice along the margins of the Arctic Ocean / by W.F. Weeks and A.J. Gow. Hanover, N.H.: U.S. Army Cold Regions Research and Engineering Laboratory, 1978.

1 v., 29 p., illus.; 27 cm (CRREL Report 78-13.)

Prepared for National Oceanic and Atmospheric Administration, under NOAA Order No. 01-5-022-1651, U.S. Army Cold Regions Research and Engineering Laboratory.

Bibliography: p. 22.

1. Arctic Ocean. 2. Crystals. 3. Ice. 4. Orientation (direction). I. Gow, A.J., joint author. II. U.S. Army Corps of Engineers. (Series: U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., CRREL Report 78-13.)